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ADVANCES IN ELECTRONIC CIRCUIT PACKAGING

Volume 3

Proceedings of the Third International Electronic Circuit Packaging Symposium sponsored by the University of Colorado, EDN (Electrical Design News), and Design News, held at Boulder, Colorado, August 15-17, 1962

Edited by **Lawrence L. Rosine,** Editor, EDN

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FOREWORD

The Third International Electronic Circuit Packaging Symposium was unique in a number of ways, particularly in its scope and in the approach taken in some of the presentations. For instance, one of the particularly interesting papers was "Designing and Packaging Electronic Modular Enclosures That Never Leave the Ground." Here we were shown how a large system console could be packaged to meet the "convenience" needs of the operator. Thus, personnel considerations became important in the package and one of the determining factors in the design.

A number of excellent papers on small packaged circuits were presented. These covered thin-film techniques, interconnections between microcircuits, methods of assembly, deposition, etc.

A lively evening session provided an opportunity for proponents of both soldering and welding to propound the merits of their respective methods. Remarks from the floor were recorded and are included in these Proceedings.

Other features of this symposium were papers on control panel packaging, methods of computing fan or blower sizes for adequate cooling, chemical milling, adhesive bonding, and seals.

Thus, all phases of packaging electronics were discussed in the individual papers and subsequent question and answer periods. In this volume, as in the previous two, we have assembled some of the most up-to-date information available in the field. We hope that readers will be able to use this information as an aid in solving their own packaging problems.

Suggestions that will help us to improve the future symposia or the published Proceedings will always be appreciated. The Electronic Circuit Packaging Symposium is held for you, the packaging engineer. You have made it a success with your papers, your attendance, and your purchase of the Proceedings.

Lawrence L. Rosine, Editor
EDN (Electrical Design News)

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Keynote Address

Ralph Leigh Clark
Assistant Director, Defense Research and Engineering for Communications
Department of Defense

I am most appreciative of the opportunity to participate in this Symposium and also to add my word of welcome. Beyond our mutual interests in the Symposium we have a great deal in common. As I judge from your program, a large percentage of the people attending are working on defense-related projects. This is to be expected as the total government procurement of electronics during the last fiscal year (which just ended on June 30) was estimated to be about 10 billion dollars. That makes it a substantial industry. Of this total, a large amount, the lion's share, was for the defense department and various defense agencies although, of course, the National Aeronautics and Space Administration and the Federal Aviation Agency use a good deal of similar equipment. You will see from my background, and from what I shall say, that most of my experience has been in the field of systems rather than in the field of components. But I have had enough experience with systems to know that systems are built up from components and that if the components do not work, neither will the systems.

My section of the office of the Director of Defense Research and Engineering is concerned with research and development related to automated support of command and control systems and long-haul communications. I will talk a little about command control because it is a subject you see in the lay press as well as in the trade press. President Kennedy has said quite a bit regarding the importance of the adequacy of command and control in some of his recent press conferences and budget messages. As we interpret it in the Defense Department, command control covers the total capability of a commander to order his forces and control his weapons, and the object of the exercise, of course, for our whole defense program is the deployment and command of weapons to keep the peace. Now broadly these systems include the commander's staff and facilities at his command headquarters, communications to subordinate commands, the staff and facilities under the control of these subordinate commanders, etc., down through the several echelons to the combatant forces. If we look at it another way, a command and control system is the sum of the people, the machines, and the organizational structure in which both work, as well as the procedures for carrying out tasks which are dictated by the assigned mission of the particular command. In this complex organization, men are assisted by automatic information processing systems (including input–output equipment and display gear) and by extensive communication systems. The communications with which we are especially concerned are those systems that tie these widely dispersed command centers together instantaneously and on a worldwide basis. The system supporting the defense command structure is made up of the communication systems built by the three military departments and the extensive transmission and switching systems which we lease from the common carriers (we lease a very substantial amount of communications capability from all the common carriers). The Defense Communications Agency, a new organ created by the previous administration just before the present administration came in, is busily putting together all these resources to form what we call the Defense Communication System, which will eventually look very much like the Long Lines Department of AT & T. This system will give ready access to the numerous channels and support many different modes of transmission.

Now in what way is our office, that is, the office of the Director of Defense Research and Engineering, concerned with this complex of problems? The Reorganization Act of 1958 assigned the Director broad responsibilities: (1) to be the principal advisor to the Secretary of Defense on scientific and technical matters, (2) to supervise all research and engineering activities of the Department of Defense, and (3) to direct and control research and engineering activities that the Secretary thinks should be centrally managed. The advisory function consists principally in giving the Secretary of Defense technical information and recommendations on broad problems that often include many important facets of the subject aside from the purely technical considerations. An example of these are the questions concerning the B-70 or the RS-70; the bomber or reconnaissance strike system about which we have seen a good deal in the press recently. Here problems may involve the proper technical performance of the system and its potential for improvement, the validity of cost and time estimates for completing the development, the assessment of possible weapon developments to counter or neutralize a new system's effectiveness, or a comparison of a new system's capabilities with those of other systems. Questions of weapons systems, military usefulness, the political and psychological implications of having or not having it, and whether the country can afford it or not are not matters generally considered in the technical field.

The director's supervisory function entails the management of defense programs on research, development, test, and evaluation (which we shorten to call RDT & E) and exerts a strong impact on the military departments and their activities. Here the director's authority is to approve, disapprove, or modify defense research, development and technical evaluation projects, and programs to eliminate unpromising or unnecessarily duplicative programs and to support or initiate promising ones. The formal procedures and techniques for screening and approving major development projects, or groups of projects, are related to the 5-year plan recently established by the Assistant Secretary of Defense Controller. In the case of major programs, decisions on research and development matters or decisions on RDT & E programs are made by the Secretary of Defense, based on recommendations of the Director. On smaller programs, the director is authorized to act in his own name. In addition to preparing recommendations on the 5-year program package each year, the Director reviews and approves the overall RDT & E program to be included in the Department of Defense budget. He also approves the release of funds to implement those programs when the appropriation acts are passed.

Recently the Director of Defense Research and Engineering was assigned more direct and specific responsibility with respect to the development of command and control systems and communications satellite systems. In the field of command-control, we will provide direct policy guidance and technical direction, review plans, assign responsibilities, consolidate the technical support budgets for the entire national military command system, and monitor the expenditures. We will continue to guide the Defense Communications Agencies (DCA) in managing systems development. The DCA has been given the responsibility for detailed system development for the national military command system.

In the communication satellite program, the job of developing and launching all space elements of the systems has been assigned to the Air Force. The ground environment is the responsibility of the Army, and the Defense Communications Agency resolves interface problems and makes certain that the system is effectively integrated into the Defense Communication System because the big problem with the communication satellite system is going to involve not only the satellite system itself but its integration into the overall communication system. The Director of Defense Research and Engineering will back up the Defense Communications Agency in its tasks and serve as arbiter in expediting the whole system.

Now this seven or eight minutes of introduction may sound a little unrelated —a bit dry to some who are concerned largely with specifics of electronic systems, etc., but I think it helps to set a background for what I intend to say next. Having set the stage by reviewing the responsibilities of the Director, let me turn to a discussion of the three systems with which my office is particularly concerned at this time: (1) automated support of command and control, (2) automatic switching for long-haul communications, and (3) the communication satellites.

These somewhat different, though related, systems have several characteristics in common. In all probability we will not have a large number of any of these systems. Quantity production will not generally be a major factor in the enterprise, although in the computers supporting the command and control systems and in the central logic and switching elements of the switching systems, there may be substantial quantities of similar modules, many of them, however, of highly specialized nature. Another characteristic of great importance is the need in all these systems for the greatest possible reliability, availability, and accuracy of operation. The technical command and control systems supporting our major headquarters must operate 24 hr a day and must be ready on a moment's notice to provide information, transmit instructions, and control operations. We cannot shut down a control center while we locate and replace a faulty module in a computer, nor can we tell the commander to wait while we find a bad transistor in the display system. Because the systems furnishing communications for the command centers are integral parts of the command support system, they have to perform with the same high degree of reliability and accuracy. When an order has to be sent from Omaha to the SAC fleet or when an air defense control center has to direct a weapon, the communications must work. If you wake up in the night and find your house on fire, the whole telephone system, including its intricate automatic switching devices, is expected to work in calling help.

There is an even greater demand for reliability with the components of communication satellite systems because once a satellite is in orbit it either operates or another one has to be put in its place. If communication satellite systems are to be economically practical for commercial uses, or even attainable for purposes of defense, the whole satellites mean-time-to-failure must be measured in terms of years, rather than months or weeks. Now, satisfying these stringent requirements poses a major challenge to the electronics industry and component selection and packaging are critical factors in meeting the requirements. The spacecraft of a satellite system (such as *Advent*, the defense communication satellite program that we have been recently supporting) contains 15,000 to 18,000 separate parts, the number depending on how a mechanical part is identified. Even though any single component may have a very long mean-time-to-failure such a complex aggregation of the presently available elements cannot be expected to have a high degree of reliability. It is apparent that although cost is always a factor in any of these systems, and anything else we procure for the government, the excellence of the product is the critical controlling element of the program. If a command center fails, or if its critical communications fail when needed, there may be no chance to repair the system and try again. If a communication satellite fails at a crucial time, essential communications will be interrupted. Since the vital element of reliability in system design starts with the electronic components, their aggregation in the circuits, and then into subsystems or system packages, the importance of your work in this field is obvious. Much is being done to understand the mechanisms of component failure and the means of improving component reliability. On the other hand, under current pressures for reduced size and weight, new processing techniques and new methods of fabricating complete electronic circuits are being developed rapidly and these pose more new problems in the control of quality and operational life.

Now, we might take a look at these command centers to see what kind of electronic machinery we are talking about. Usually there is a large computer that most of you would recognize by name—an IBM 7090, CDC-1604, or a comparable product of Philco, Sylvania, Burroughs, or other equally competent manufacturer. Some of the centers may also have perhaps as alternates or as essential parts of the systems specialized computers, such as the Sage FSQ-7 or the FSQ-32 of SAC-465L system. Ordinarily there is extensive auxiliary tape storage and often high-speed disc memories. Sometimes a specialized computer is needed for switching between computers, because more and more of these centers are using a number of computers to perform different jobs in order to increase the basic capacity, improve reliability, and eliminate down-time.

In command centers we also find extensive modulation, demodulation terminals to handle direct-stream data, teletype inputs, or other inputs. The usual card punches and other manual input devices will also be there. Some systems, such as 465L, will have a complex communication switching center with built-in stored program control to cope with the great volume of incoming and outgoing messages and to route local information. Now parts of these systems are what we call "on-line," that is, they are performing functions 24 hr a day every minute of the day—functions that have to be performed if the command is going to operate. These are similar to the communication systems. There are other parts that operate "off-line," that is, computers that aid in planning and management of logistics, etc. They do not have to be instantaneously available so in a command center you really have two types of operations. The "on-line" portion of the system is the really critical part. On the output ends of these systems we will have all sorts of printers and display systems. Some of the most challenging and interesting are the electromechanical devices that present large wall displays of the information for use of commanders and their staffs. Here the reliability problem is quite different from the one that faces the designer of an electronic circuit module made up of simple electronic components such as resistors, condensers, diodes, transistors, or a stack of thin-film or solid-state elements. Some of these electromechanical systems have to handle large numbers of film chips or slides that are used to project information on screens. They have cathode-ray systems to prepare new slides based on computer information. You have to shunt these slides around within the machine, store them, retrieve them on call, etc.—so there are plenty of headaches.

We deal with matters relating to communication systems separately from command and control problems chiefly because they serve many needs not pertinent to the central command structure, but when we take a careful look at the developing control and receiving centers and particularly at the switching centers, their similarity to big computer centers is very striking. So, even though we handle the communications problem somewhat separately, the technologies involved have very much in common. We are developing switching systems to meet the needs of a continually widening variety of communications which range from teletype at 60 words per minute through card data, medium-speed stream data, voice facsimile to high-speed data at 40 to 50 kilobit rates. We will use space division analog switches, extensive systems of time division digital switches, and at many centers a large store and forward system that will accept, store, and route record types of communications, including teletype, cardlike traffic, many classes of data, etc. The problems of these switching systems relative to components, systems modules, and packaging will be the same as those of computers in a similar environment. Again these communication systems are "on-line" systems with the most stringent requirements for reliability and availability. We may find some variations in components, for instance, some of the ferreed and solid state switches used in the circuit switch systems. These familiar problems will no doubt be discussed again during this Symposium.

At present we are meeting the demands for reliability and operational continuity in command and communication systems with a combination of reliable circuit designs, programs on component reliability and selection, automatic bypassing or substitution of defective modules or subsystems, automatic indication and location of component failure, and major system redundancy. In one communication system, for example, we use a complete duplicate central logic unit, very similar to the RCA-501 to manage the system; one "on-line" and one as a backup "off-line" at all times. This poses a major problem in the software (programming side), of switching from the operating unit (which may go bad) to the standby unit. So we have problems there.

In one of the command systems, the 465L system, again we have a complete duplicate central logic system in order to increase the reliability to a maximum, but here again we have the problem of transferring from an "on-line" central processer to a standby central processer losing the minimum of information and with the minimum down-time. All of these measures are complex and expensive; but these systems, of which luckily for us at least, there are not too many, must work at all costs. Certainly, there will be less than half a hundred command and control centers and major switching centers throughout the world.

Now, as we said, communication satellites have a whole new set of reliability problems. Here is a grossly different situation for considerations of weight place very stringent limits on the excess baggage allowed beyond the minimum essential circuitry to perform the mission. It costs thousands of dollars a pound to put this stuff in orbit and in certain of the most valuable orbits, such as the synchronous-equatorial orbit, there are severe absolute limits at the present time on the weight that we can lift in one package. There is no servicing of a satellite once it fails. One of our suppliers warrantees a traveling-wave tube for 7500 hr, but he says, "If it fails I can't go fix it." As you may have read lately in the trade press and in the record of congressional hearings we are realigning our space communication program and we are doing this mainly because of what we have learned in the last 3 years about the problems of weight and reliability.

We recently phased down the *Advent* program from a full-scale system development to a study of component reliability and a series of component and subsystem tests. In place of the 1300-lb *Advent* spacecraft we will develop one weighing about 500 lb on a somewhat longer time scale. In addition, we will start to develop a satellite for a simple multiple satellite system with the birds operating at medium altitude orbits, that is, 5000 to 10,000 or 12,000 miles. We are beginning work on this latter system because we are confident that the reliability of the really simple satellites is here and that we can feel confident of getting a system in operation fairly soon. This decision was made well before the *Telstar* launch; however, its success gives us more confidence in a simple design using the best available components, carefully selected and aged, and with a minimum of redundancy.

Before we can afford to continue using the medium-altitude multiple satellite system, the mean-time-to-failure of each bird must be stretched to 2 or preferably 5 years. I might illustrate by saying that if you set up a system that required 40 satellites in orbit to be reasonably effective—40 satellites in medium orbits will not give continuous service on all the channels we need, but it will give us very useful service. To put a system of 40 satellites in orbit, let us say you can launch five with one vehicle, you have a mean-time-to-failure of 1 year, and your success of launch is 8/10. You are going to have to make 10 launches a year (50 satellites a year) to have hope downstream about three years of having 40 active satellites in orbit. Now, you folks that are in this business know what 10 launches of an *Atlas Agena* type vehicle will cost per year. This is a problem on the defense side of the house, it is a problem in the thinking on commercial communication satellite exploitation.

Also, before we have a really reliable, dependable, synchronous satellite system we have to have the same life expectancy because here the cost of launch is going to be much more, the birds are going to be much more complex because we have complex electromechanical propulsion, stabilization, position-keeping systems, and the communication package is much more complex. Now these, gentlemen, are some of our problems. The critical factor of system reliability affects every aspect of a space communication system. It starts with a synchronous satellite orbiting at 22,300 miles above the equator, has to be headed in the right direction at a velocity that is correct within a few feet per second, and capable of staying right side up, pointing in the right direction, and staying in the right place for 2 to 5 years. It extends all the way back to the processes of refining basic materials and their fabrication into circuit elements and small mechanical parts of the system. Between these extremes, at the level of circuit assemblies, lie some of the heaviest responsibilities for reliability. At any point along the line, in selecting parts, designing circuits, or producing them in quantity, we can succeed or fail in this struggle for reliability.

I believe that the areas of raw material refinement and the perfection of processes for fabricating components and devices offer great opportunities for improving the reliability of our systems. First we must perfect methods, such as those specified for *Minuteman,* to ensure component reliability with various types of module assemblies now being developed and amply illustrated in your program. We then must go on to the use of thin-films, planar diffused circuits, and perhaps even to molecular circuits. Some of us believe that once we have mastered techniques for controlling the quality of raw materials and the fabrication or formation processes for producing these new kinds of circuits, we may attain higher orders of reliability than are possible with components now available. In fact some of the first data on reliability of silicon circuits show that the failure rate of silicon circuits, about as complex as circuits with 20 conventional components, is of the same order of magnitude as that of a single transistor. If we can effect a 20 to 1 improvement, this is a tremendous jump.

Certainly our problems do not lack variety and interest. They range all the way from the environment of immersion in sea water with all of its cooling capabilities, etc. (I notice you have a paper on your agenda concerning components for use in oceanography) to the hard vacuum of far space. Your contribution to their solution is critical to the future of the command and communications systems that we must have to survive and to the success of our manned and unmanned exploration and use of space.

This Symposium, for which many people pioneering in the design and construction of advanced electronic modules and systems have come together, should make a valuable contribution toward overcoming the difficulties of creating reliable long-life systems.

1405 Printed circuit boards
Encap. compound
Injection molded shell
Flexible printed wiring

Economic Aspects of Display Panel Packaging

ROBERT O. LINK
Electronic Systems and Products Division, Martin Company, Baltimore, Maryland

This paper describes a balanced design approach established at the Electronic Systems and Products Division of the Martin Company. Included are several economic evaluations to illustrate the advantage in using this approach during the design phase.

INTRODUCTION

MODERN PACKAGING presents a complex design problem in terms of producibility, maintainability, density, weight, reliability and appearance—stressing a tight schedule throughout. In an effort to satisfy these requirements, there is usually insufficient time for economic evaluation, the common argument being the need for special technical assistance.

The Electronic Systems and Products Division of the Martin Company has established a balanced design approach to technically assist and support the designer in the areas of Human Factors, Reliability, Maintainability, and Value Engineering. This paper describes the procedure and application of the Value Engineer in an actual program.

PROCEDURE FOR ECONOMIC EVALUATION

The analytical evaluations, essentially function-oriented, consist of three main steps:

1. Definition of function.
2. Creation of alternate design approaches.
3. Economic comparison of alternate design approaches.

Definition of the function, the most important phase of an evaluation, will distinguish necessary requirements from those that are advantageous but unessential. A close study of the design parameters and a parts requirements discussion will establish the optimum concept standards.

At this point, suggested alternate design approaches are discussed with all those directly related to the design function (especially the design engineer) and those responsible for maintainability, reliability, and value engineering. These preliminary design sessions may create three or four concepts to be considered and analytically evaluated.

The alternate design approaches are then tabulated and analyzed step by step, and the total cost is computed. Because the comparison is prepared in the preliminary design stages, it is desirable to present the evaluation informally with sufficient documentation for the decision makers; a formal document containing the necessary major breakdown is issued later, detailed backup data being filed.

Comparisons may be conducted by either of two methods:

1. Method A, the most effective short-cut method.
2. Method B, the detailed breakdown.

Method A is most valuable when the analysis is urgently needed during the proposal or preliminary design stage of a production design program. The alternate design approaches normally have some items that are comparable and therefore merely may be itemized as conditions of the evaluation. All noncomparable items are tabulated and accounted for in the analysis.

It is necessary to utilize Method B, a detailed cost breakdown which considers all anticipated costs in order to obtain a predicted cost for all the alternate design approaches, if a detailed total cost breakdown is a program or documentation requirement. This method considers all recurring and nonrecurring in-house costs in addition to outside vendors' costs and shipping costs. This type of study, normally unacceptable when time is critical, has more value than Method A when conclusive data are needed to complete a similar study or for use in a detailed comparison with a new concept being introduced in another program.

VALUE ENGINEERING DURING THE CONCEPTUAL STAGE OF PACKAGING

To define the economic aspects of display panel packaging, a digital monitor and control device will be used to illustrate economic evaluation during the conceptual packaging design phase. This phase is emphasized by the Value Engineering effort, a vital control in producing the optimum design.

The program required 200 display panels with 195 dual lights per display panel, including associated logic. The logic requirement was to provide display output interlocked with input. The initial approach, conventional and easily adaptable to the problems of packaging, was based on the knowledge and facilities provided by experience (Fig. 1). The display consisted of 13 vertical chassis with 15 dual-light displays per chassis, each chassis incorporating front panel with handles; support for connectors, harness and printed wiring boards; and lights, connectors, harness, and module logic printed-wiring boards.

As a result of good value-designer teamwork during preliminary design, a completely new concept evolved: Rather than mounting logic modules on printed-wiring boards and interconnecting the lights, modules, and connectors with wiring, they were combined into one component as shown in Fig. 2. The dual lights, mounted in the front face of a shell, were wired to the logic module (also housed

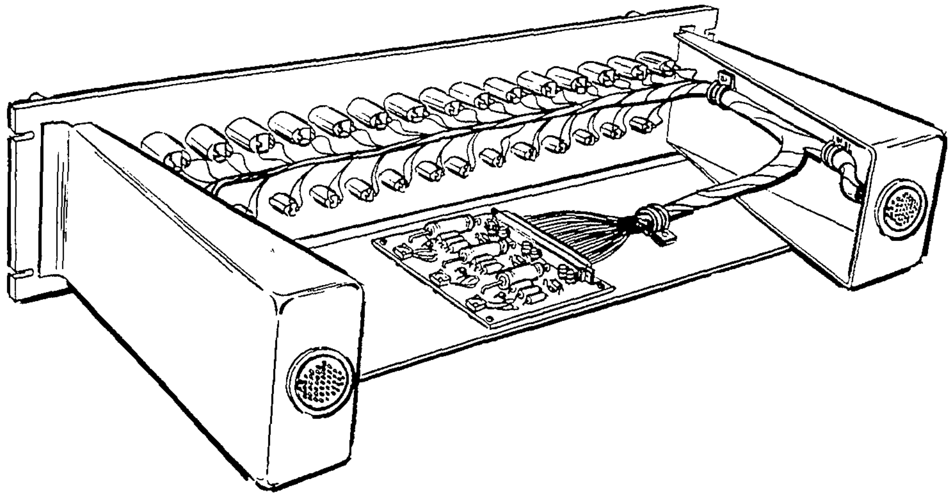
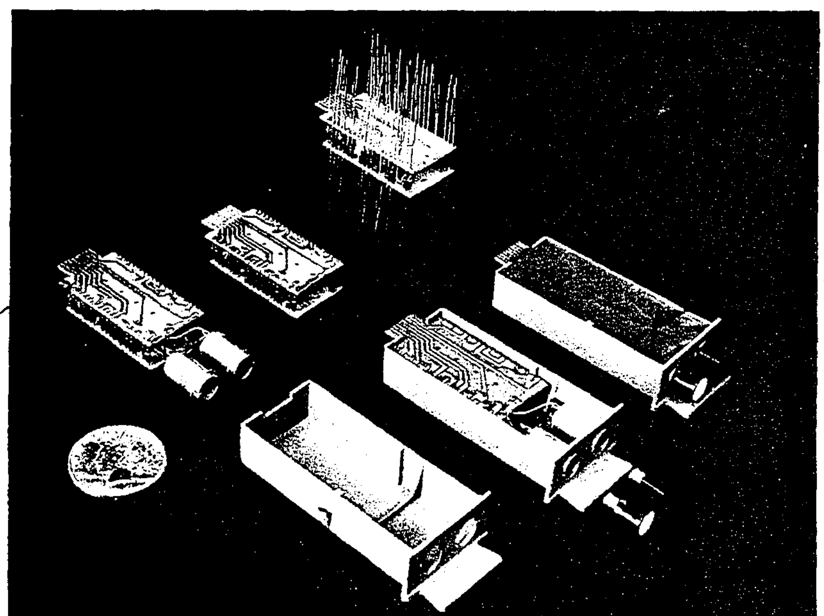


Fig. 1. Conventional chassis.

in the shell). All input and output signals to the logic module were interconnected to the logic module's upper printed-wiring board, which was extended beyond the back edge of the shell, using the board as an edge-type connector. All interconnections, rather than requiring wiring harness assemblies for each chassis and chassis interconnection, were then accomplished in the chassis matrix.



printed circuit

Fig. 2. A dual light module.

injection molded plastic shell

This concept, obviously lessening the complexities of the initial approach, also presented many economic problem areas. The following section illustrates the application of economic analysis to complement design decisions in these areas.

ECONOMIC STUDIES CONDUCTED DURING THE PRODUCTION DESIGN PHASE

Because the packaging concept is determined during the preliminary design phase, Study No. 1 deals with the largest structural item and effects a saving of $7364. The other studies, conducted in the packaging areas of interconnections, are aimed at reducing the high recurring costs of manufacturing wire harness assemblies at the chassis, display panel, and rack interconnection levels.

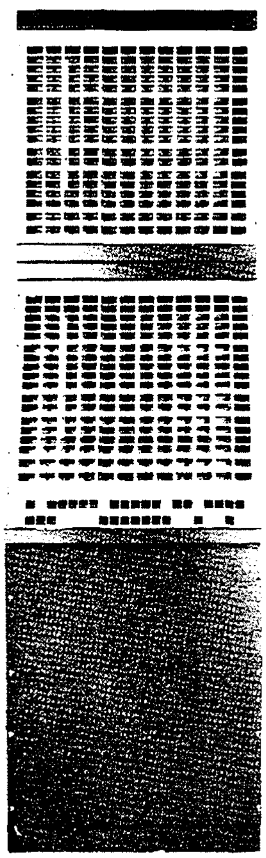


Fig. 3. A module support structure.

Study No. 1

The design objective is to determine the most economical structure to support 195 light modules in a display panel. The density of the light modules dictated three design alternates.

1. Design No. 1 comprised a sheet metal box with a separate front panel containing 195 cutouts for light modules.
2. Design No. 2 comprised a sheet metal box with 11 vertical molded plastic partitions to support light modules.
3. Design No. 3 comprised a sheet metal box of interlocking egg-crate construction to support light modules.

After a detailed comparative cost analysis (presented in Memorandum No. 1), Design No. 1 (Fig. 3) was recommended and adopted as the most economical

VALUE ENGINEERING MEMORANDUM — No. 1
Date 2-9-62

PROJECT XXX

To: G. W. Krowl
cc: H. J. Reis, J. Wender, J. Spencer
SUBJECT: Structure Configuration for Display Control Panel in Rack

---

1. OBJECTIVE:
   To determine most economical structure to support 195 light modules.

2. ALTERNATE:
   Design No. 1: Sheet metal box with separate front panel containing 195 cutouts for light modules.
   Design No. 2: Sheet metal box with 11 vertical molded plastic partitions to support light modules.
   Design No. 3: Sheet metal box with sheet metal interlocking egg-crate construction to support light modules.

3. DISCUSSION:
   The comparative cost analysis is based on the following conditions:
   a. All sheet metal parts are low-carbon cold-rolled steel.
   b. The rear panels for all designs are comparable and excluded from this analysis.
   c. All manufacturing and tooling costs are estimated actuals.
   d. Provisions for lettering on front face have been excluded from this analysis.

4. ACTION:
   Design No. 1 was recommended as the most economical alternate design and adopted for design.

5. SAVINGS:
   Design No. 1 represents a total savings of $7364 over Design No. 2 and a total savings of $3870 over Design No. 3. These savings are based on a quantity of 200 display control panels.

DEPT. 3540—Value Engineering
ANALYST: R. O. Link
APPROVED: R. E. Parsons

design. It effected a total savings of \$7364 over Design No. 2 and a total savings of \$3870 over Design No. 3.

Although this study involves the largest structural area, the relatively small savings indicates the packaging area will provide greater savings as proven in Studies Nos. 2 and 3.

Study No. 2

Study No. 2, conducted to determine the most economical wiring technique for display panel interconnections, considered three possible design alternates:

1. Design No. 1 comprised 195 printed wiring "edge-type" receptacles mounted on a 21 × 24-in. sheet metal rear panel, all interconnections being wired by the conventional "hard-wire" technique.
2. Design No. 2 comprised 195 printed wiring edge-type receptacles mounted on a 21 × 24-in. rigid printed-wiring board for all interconnections.
3. Design No. 3 comprised 195 printed-wiring edge-type receptacles mounted

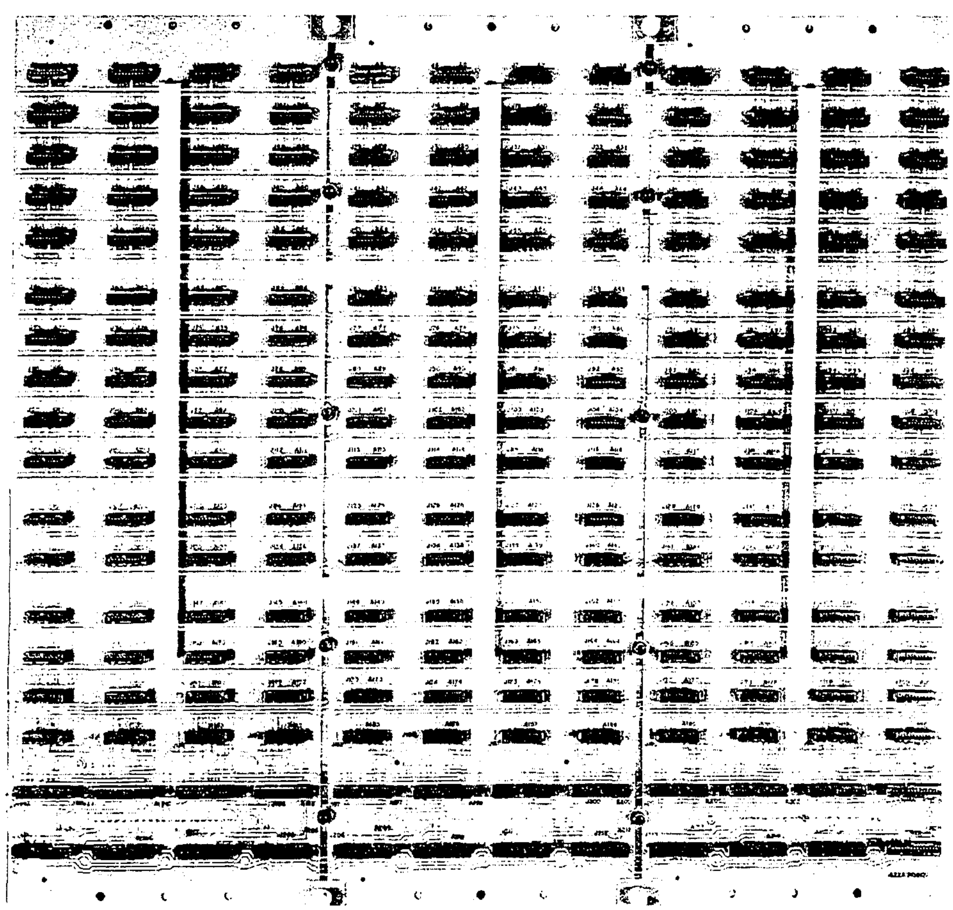


Fig. 4. Printed-wiring interconnection board.

on a 21 × 24-in. sheet metal rear panel utilizing tape cable or flexible printed circuit technique for all interconnections.

Study No. 2 indicated that Design No. 2 (Fig. 4) represented a total savings of $140,000 over Design No. 1 and a total savings of $74,000 over Design No. 3. Memorandum No. 2 details the results of this analysis.

VALUE ENGINEERING MEMORANDUM No. 2
Date 2-22-62

PROJECT XXX

To: G. W. Krowl
cc: H. J. Reis, J. Wender, J. Boegner
SUBJECT: Wiring Technique for Display Control Panel

---

1. OBJECTIVE:
   To determine the most economical wiring technique for interconnections on the display control panel.

2. ALTERNATES:
   Design No. 1: Mount 195 printed circuit (edge-type) receptacles to a 21 × 24-in. sheet metal rear panel and wire all interconnections by conventional "hard-wire" technique.
   Design No. 2: Mount 195 printed circuit (edge-type) receptacles to a 21 × 24-in. rigid printed circuit board for all interconnections.
   Design No. 3: Mount 195 printed circuit (edge-type) receptacles to a 21 × 24-in. sheet metal rear panel and utilize tape cable or flexible printed circuit technique for all interconnections.

3. DISCUSSION:
   The comparative cost analysis is based on the following conditions:
   a. The rear panels for Designs Nos. 1 and 3 are low-carbon cold-rolled steel.
   b. All manufacturing and tooling costs are estimated actuals.
   c. Connector assembly time is based on the use of eyelets for attachments.

4. ACTION:
   Design No. 2 was recommended as the most economical alternate design and was adopted in the design concept.

5. SAVINGS:
   Design No. 2 represents a total savings of $140,000 over Design No. 1 and a total savings of $74,000 over Design No. 3. These savings are based on a quantity of 200 display control panels.

DEPT. 3540—Value Engineering
ANALYST: R. O. Link
APPROVED: R. E. Parsons

Study No. 3

Study No. 3 consisted of an investigation of techniques of interconnections for a display bank rack. Two design alternatives were investigated:

1. Design No. 1 involved using conventional "hard-wiring" techniques for interconnection of chassis and display panels in a sloping front rack.
2. Design No. 2 involved using tape cable technique for interconnections between the chassis and display panels in a rack.

This study indicated that Design No. 2 (Fig. 5) represented a savings of $69,000 over Design No. 1.

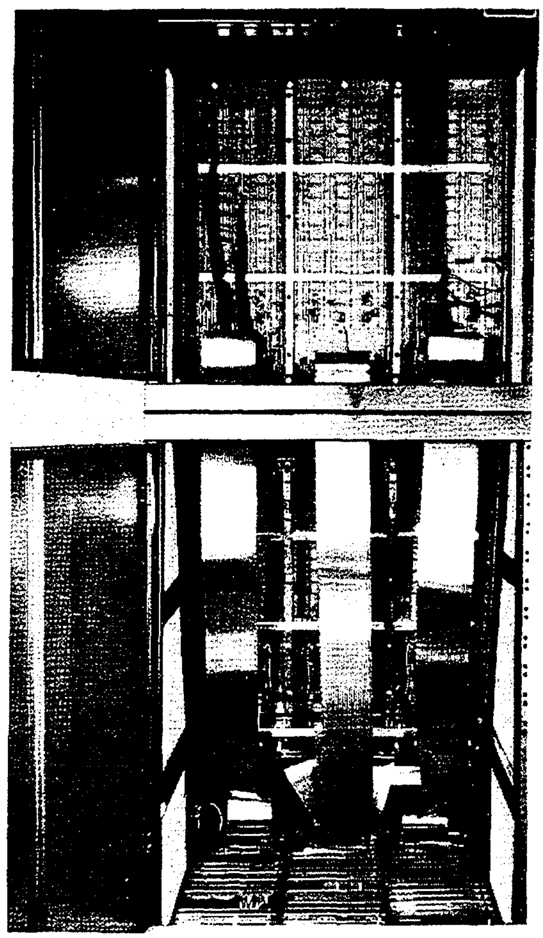


Fig. 5. Tape cable rack interconnections.

This study, presented in Memorandum No. 3, did not follow the normal procedure because in-house techniques were not available for tape cable fabrication. Consequently, vendors were contacted to formulate the data needed for a cost analysis. A later investigation of tape cable harness fabrication indicated the need for and subsequent installation of fabrication facilities.

VALUE ENGINEERING MEMORANDUM — No. 3, Date 3-12-62

PROJECT XXX

To: G. W. Krowl
cc: H. J. Reis, J. Wender, C. E. Dawson, J. Boegner
SUBJECT: Wiring Technique for Display Bank Rack

---

1. OBJECTIVE:
   Determine the most economical wiring technique for interconnections in the display bank rack.

2. ALTERNATES:
   Design No. 1: "Hard-wire" interconnection in the display bank rack.
   Design No. 2: Use "tape cable" for interconnection in the display bank rack.

3. DISCUSSION:
   The cost analysis is based on the following conditions:
   a. Clamping and harness tying provisions not included.
   b. Reel-fed crimp-type contacts used for the receptacles in Designs Nos. 1 and 2.
   c. The display bank rack contained the power supply, message composer, command control panel and two display panels.

4. ACTION:
   Design No. 2 was recommended as the most economical alternate design and was utilized in the design phase.

5. SAVINGS:
   Design No. 2 represents a total savings of $69,000 over Design No. 1, based on a quantity of 200 units.

DEPT. 3540—Value Engineering
ANALYST: R. O. Link
APPROVED: R. E. Parsons

CONTINUED APPLICATION OF SOUND CONCEPTS

Additional items are presented to illustrate the value of utilizing early design decisions in guiding later packaging concepts without repeating similar economic studies.

The digital readout module (Fig. 6) illustrates the adaptation of three digital readout components to the packaging concept adopted for the dual light module (Fig. 2). An investigation by the designer revealed that the digital readout component was not available as a plug-in component and would require adaptation. The digital readout components were designed for use of conventional wiring techniques, and, therefore, a transition had to be made from hard wire to printed wiring board. The module then could be replaced easily and could be mixed with other light modules on the display panel.

The complete digital readout module consists of a molded shell, three spring clips to retain the three digital readout components, three digital readout units, jumper wires, and a printed-wiring board.

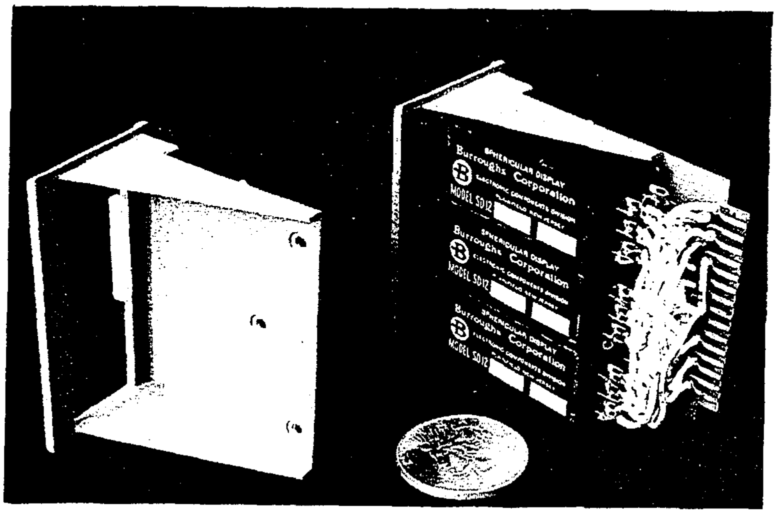


Fig. 6. A digital readout module.

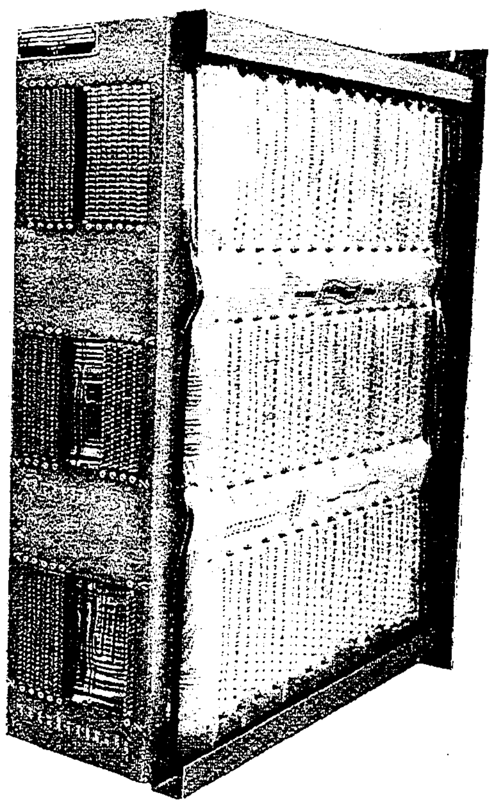


Fig. 7. Flexible printed wiring chassis interconnections.

The logic module card chassis (Fig. 7) illustrates the use of flexible printed wiring for interconnections at the chassis level. Because Study No. 2 (Fig. 4) indicated that conventional wiring was the costliest technique, this conclusion also applies at the chassis level. Initially, a rigid printed-wiring board was considered, but it required a costly multilayer board and interconnections within the chassis from the rigid board to the chassis connectors. Vendors supplied flexible printed wiring with logic module card connectors and chassis connectors attached. The cost was substantially lower than that of conventional hard wiring. Additional savings were realized by requiring the vendors to perform continuity tests of the flexible wiring prior to shipment.

This paper presents a few economic evaluations to illustrate the advantage in using this approach during the design phase. The value study has been accepted at Martin ESPD as a normal design input and the basis for many design decisions, because acknowledgment and acceptance of sound economic evaluation techniques lead to a finer product at a competitive cost.

DISCUSSION

Q. (Duane Aubrey, General Electric Co., Syracuse, N. Y.) My question concerns the repairability of the dual light modules. It seems to be quite a dense package with many components. How did you factor in to your cost analysis the in-process losses of the module after encapsulation?

A. We had a target cost figure established at the onset of the program of $10.00 or less as a low-cost, throwaway, nonrepairable concept.

Q. (Ordean Joachim, Univac, St. Paul, Minn.) My question deals with the construction of the dual light module. What dictated the choice of the cordwood construction over the conventional method of single-side laminate or double side? Judging by the number of components, it didn't look as though the cordwood construction was necessary in all cases.

A. In a coordinated effort with manufacturing, we found that an appreciable savings in assembly/circuit function could be realized using peripheral mounted components rather than the conventional method of inserting component leads through holes in the cards.

Q. (Charles Mason, Raytheon Co., Bedford, Mass.) How did the value engineer optimize the electrical circuit diagram?

A. On our staff at Martin-Baltimore, we have an electrical engineer with considerable circuit design experience, and his function on the staff is to do just as I stated. He analyzes the basic circuit function together with the designer to determine the optimum circuit and select low-cost components which are unknown to many circuit designers.

Q. (David Walker, Sperry Gyroscope, L. I., N. Y.) Do you have a comparison between the estimates and the actuals for these evaluations?

A. Yes, the actuals were obtained from our I.E. Department.

Q. (Jim Casey, Hughes Aircraft Co., Culver City, Calif.) How did you get the design department to submit three proposals? If project management imposes this requirement on a design department, do you not get one good proposal and two rather half-hearted ones?

A. No. In our preliminary design phase, meetings are conducted where we narrow down to two or three alternates. They are weighed against each other with inputs from the value engineering group, reliability, maintainability. Another meeting is held with project management represented to arrive at a final answer.

Q. (Lou Critelli, General Electric Co., Utica, N. Y.) I noticed you have certain types of chassis in the assembly. You made no comment on what they were or what effort was made in the choice of the fabrication or molding.

A. The chassis shown in the rack is a logic chassis for signals to the dual light modules on the display panel. A value study recommended the use of a low-carbon steel bent up chassis with die-punched slots to support the module mother cards. This design was adopted on the program.

Q. (John Saul, Temco Electronics, Dallas, Texas.) I noticed that in the digital readout module you have here, the wiring from the terminals to the printed-wiring board make it a plug-in unit. Is there any reason you did not eliminate that wiring, in other words, purchase the little Burroughs units with the longer-wire leads and go straight into your board and eliminate that additional wiring?

A. This was investigated at the time this study was conducted, by contacting a Burroughs representative and at that time there were no components available to do this.

Q. (Wayne Franklin, Lockheed Missiles and Space Co., Sunnyvale, Calif.) I noticed that your choice of enclosure for the module was a casting. Were the economic aspects of purchasing prefabricated enclosures considered?

A. The enclosure for the module is an injection molded plastic shell manufactured at Martin-Baltimore as a result of make or buy decisions.

Q. (Harry Bendtsen, Paraplegics Mfg., Chicago, Ill.) What is your assembly time compared to labor time when you have so many modules? Can you get the test time down sufficiently to make it a profitable item compared to a short-run production?

A. Let me direct that question to Mr. Schehr, representing ESPD Manufacturing, Baltimore . . . (Mr. Schehr) The production line was a series run paced conveyor operation. Each operator placed a half-dozen parts across the notched cards. The lines cycled at ½ min. The module was run on the line 8 min and total labor time was 12 min. The test was in series at the end of the conveyor after dip solder. Test time was 20 sec.

Q. (George Hayashida, Ampex, L. A., Calif.) What was the elapsed time from the original concept of the design to the engineering release?

A. Two months.

Q. (Ellis Gottlieb, Westinghouse, Baltimore, Md.) Who assumes the final responsibility for these committee decisions?

A. The program manager, or his representative, assumes responsibility for "trade off" decisions.

Q. (Dick Anderson, Fairchild Defense Products, Palo Alto, Calif.) Do you have any data on the reliability of the plug-in modules with their 195 connectors as opposed to welding or soldering or wire wrapping in place?

A. No, we don't have the reliability figures for one *vs* the others; however, the value optimized approach presented does meet the reliability requirements of the program.

Designing and Packaging Electronic Modular Enclosures That Never Leave the Ground

VINCENT J. GALATI
System Development Corporation, Santa Monica, California

This paper describes several creative and unusual packaging techniques for large and complex consoles. Design approaches and implementation are discussed.

INTRODUCTION

CREATIVITY PLAYS a large role in the techniques applied to designing enclosures and consoles. This certainly does not mean that all designers should be Edisons, but too many Design Engineers today "catalog" an entire design with the result that their engineering talent has been lost in a world of salesmen, catalogs, purchasing agents, and the like. There is a need for this liaison, but as a Design Engineer, one should allow himself some latitude to apply novel and unique ideas to his creation. To do this, one philosophy can be kept in mind: "*TO SATISFY, SIMPLIFY*." This dictate, if considered carefully, carries many implications when applied to five general categories associated with newly designed equipment. These categories are operation, maintenance, construction, installation, and appearance of the finished product.

This paper illustrates how this design approach was used in the repackaging of an existing facility into one enclosure; and again in the construction of a large control console. The result, in either case, was a distinctive piece of equipment that met a demand for custom appearance at relatively low expense.

It should be mentioned that the Engineering Department of the System Development Corporation does not have a product of any kind that reaches a market in the "outside world." Our efforts are totally directed toward providing corporation research scientists with advanced and particular devices used to impart specialized scientific and technological services to agencies of the United States Government, state and local Governments, and educational and scientific institutions.

We maintain a highly impartial relationship with the rest of the industry in order to retain their respect, protect their proprietary interests, and assure them there is no conflict between their goals and ours. Even within this environment of impartial relationships, the pressures of budget, schedule, and customer satisfaction still exist, perhaps more so than in profit-making industries.

In computer-based facilities, there are times when peripheral equipment is temporarily installed to investigate extended capabilities of a given system. Modifications and additions are implemented, and the installation begins to look like a well-stuffed garage. If the equipment is proven and accepted as part of the subsystem the Design Engineer is called in to repackage the mess. The Magnetic Tape-to-Cathode Ray Tube equipment at the System Development Corporation, shown in Fig. 1, was a typical case. This equipment is used in the preparation of radar training films for the United States Air Force. It had expanded to eight large racks of control equipment and power supplies, one IBM 729 magnetic-tape transport and a Mitchell 70-mm camera. The camera was table-mounted over a 7-in. precision cathode ray tube. Repackaging this accumulation of complex equipment presented quite a challenge. Let us examine this challenge in some detail.

A cursory survey showed that we could leave the IBM 729 tape transport and the camera assembly as two separate units, and concentrate on enclosing the control equipment and power supplies in one console. This decision was acceptable as the tape unit and the camera assembly were neatly packaged and only required a redressing of cables.

The next step was to evaluate all the considerations involved in the final design. Although there were many, many parameters to be considered for this design, most of them had one distinct facet: *simplification*. Regardless of where, or from whom, the design input was solicited, there was always the same basis for the requested change. "Simplify it, make it easier, it's too complicated now; *we could do a lot more if it weren't so complicated.*" The last was heard often and from many sources.

This led to one conviction: Simplicity in design would facilitate the operation and maintenance of the equipment; and obviously, if the design were simplified, it would ease the overall project effort. We also recognized that this design approach would lead to *low costs*, both current and future. We resolved to use this approach throughout and observe the effects when applied directly to a complex design task. The results were, and still are, extremely encouraging. So much so that they have been attributed to our acceptance of the aforementioned philosophy, "To satisfy, simplify."

One curious side effect occurred when we attempted to apply this philosophy to the numerous design inputs. It could not be used on the single requirements because the individual designs sometimes conflicted and resulted in a direct opposition to our philosophy. But when the same requirements were considered with operation, maintenance, construction, installation, and appearance of the *finished product* in mind, we were able to apply the philosophy generously and harmoniously. Although appearance certainly plays a large role in all of the preceding categories, we chose to define it as an entity, and place it in this position in answer to one question: "Will this console be appealing and pleasant to look at when completed?"

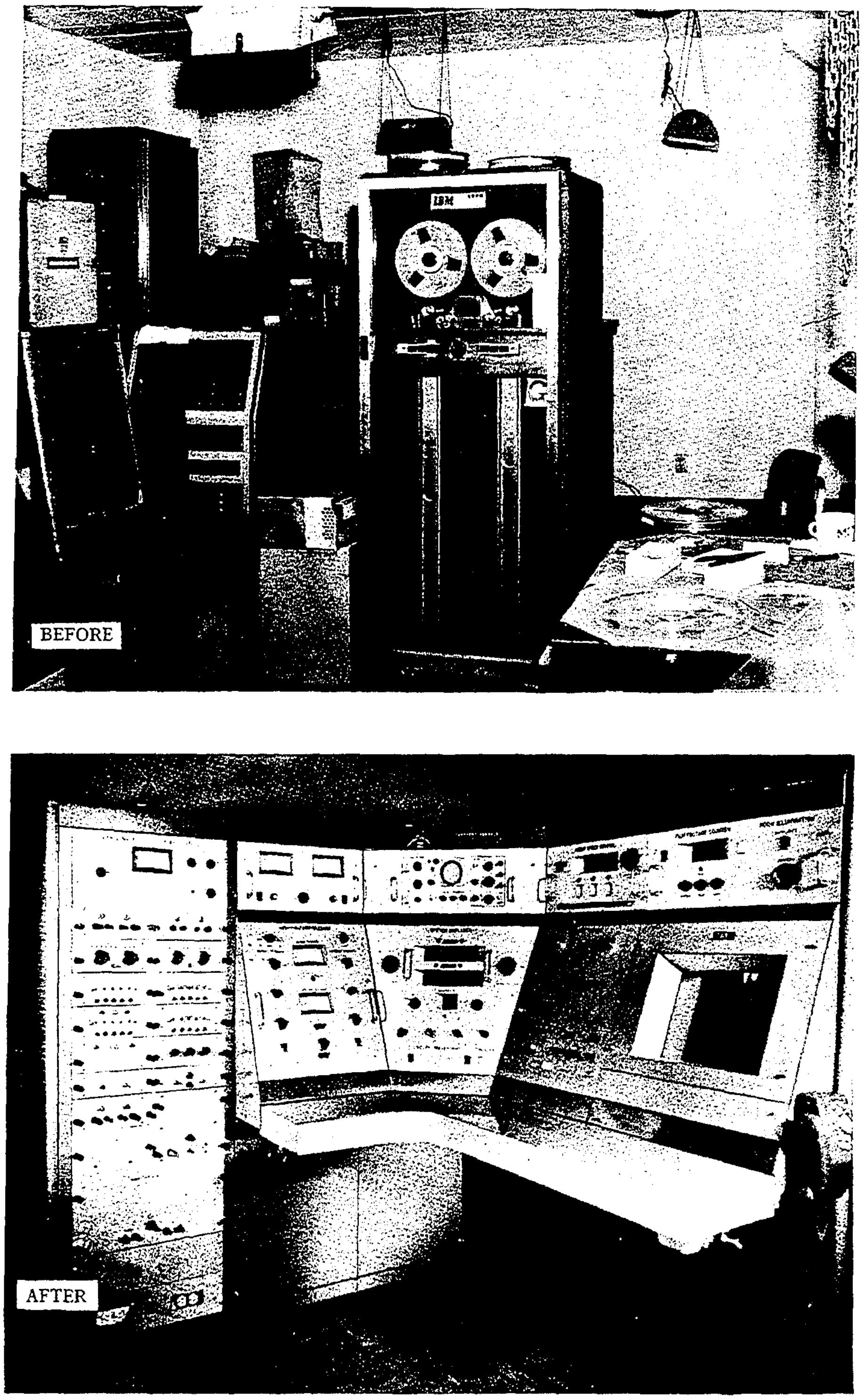


Fig. 1

All of the equipment required quite a bit of panel space. The console and panel area was divided into three sections as shown in Fig. 2. One section served the operator and was placed at the right side of the console, which put his working area adjacent to the tape drive and camera. His panel area was simplified as much as possible. All complicated metering was eliminated. Numerical monitoring was provided by direct-reading projection indicators mounted as close to the line of sight as possible. This provided rapid reading for the inexperienced operator. Most often used switches were placed between elbow and shoulder height. All danger signals were red, brightly lit, and in an area that was not associated with any other control function. For a system error, e.g., tape signals incorrect, a large blinking red light was used, which remained on until the trouble was corrected. Any other metering that had to be observed by the operator was arranged for straight-line indication on large-face dials, with red-light alarms for incorrect voltage readings. Several lines of communication were provided by a phone within easy reach. A counter was placed in front of the console to give the operator ample writing surface. This was positioned at desk-top height. Since careless scattering of cigarette ashes can contribute to the malfunctioning of tape drive systems, we provided built-in ash trays and cigarette lighters. Room lighting was controlled by a dimmer located on one of the front panels of the console. Dimming

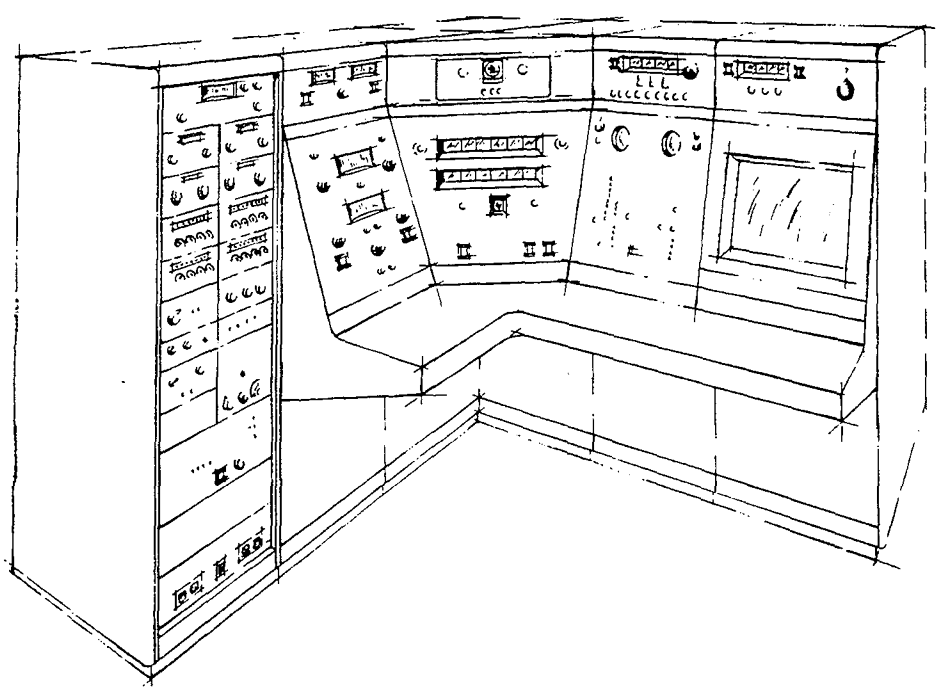


Fig. 2

the lights relieved eye strain in viewing the 21-in. monitor which had a blue phosphor. Also, bringing the light down to a nonglaring level reduced operator fatigue.

Since the camera contained raw 70-mm film, the doors of the room and the CRT observation panel presented film-fogging hazards. To prevent accidental fogging, the operator was provided with master switches on the console next to the dimmer to give him the option of darkening the room entirely, or lighting the room with appropriate safe filters for the type of film being used. Master turn-on procedure for the operator was one simple push of a button. All voltages were appropriately time-delayed and put on sequentially and automatically. An executive chair was provided for operator comfort.

The left side of the console was designed for maintenance purposes. All preventive maintenance adjustments, metering, and checkout functions were adequately indicated, metered, and accessible. They were positioned so that the maintenance man performed his normal function from left-to-right, top-to-bottom. All chassis with front panels attached were either on slides or hinges to provide good accessibility. One problem area was the panel mounted on the 21° sloped-front turret. As all designers know, very little has been done to provide a means of bringing this type of panel straight out with a chassis attached. This problem was solved by a novel invention as shown in Fig. 3. A standard chassis track was mounted at right angles to the bottom of the panel. A pivot pin was positioned several inches back in the chassis line, on the immovable part of the chassis track. Pulling the panel forward, carried the chassis out at the 21° slope. When the chassis center of gravity was beyond the pivot point, the chassis and panel would drop down to a horizontal movement. It would remain in this position until the chassis was fully extended, then lock automatically. Two hinged detents were located on top of the chassis, close to the panel. Releasing these detents allowed the panel and chassis to rotate down 90° from the horizontal, exposing the complete chassis to the maintenance man. Since this was a 10,000-v bleeder, it required some arcing and safety precautions. Plexiglas was used throughout; hermetically-sealed, glass-encased resistors were used; nylon shafting, brought forward to the front panel, was used for all controls and adjustments.

The cabling to this chassis presented another problem. These cables, which were tied directly to the cathode ray tube, required high-voltage co-ax. The cable dressing, to allow the kind of chassis movement we required, had to be unique. The answer was a commercially available neoprene-covered co-ax that carries two integral steel stiffening strips placed 180° laterally along the cable length. This construction allowed the cable vertical movement only, as indicated in Fig. 3.

Returning the chassis to position was almost the reverse of the removal procedure, with one exception. The panel and chassis were returned to the horizontal, locked in place, and the entire assembly—panel, chassis, and chassis track—was lifted $\frac{1}{2}$ in. and pushed back. At the appropriate place in this movement, a trigger was pulled automatically, dropping the back end of the chassis so it would slide in at the 21° angle. All this was done with one sweeping motion.

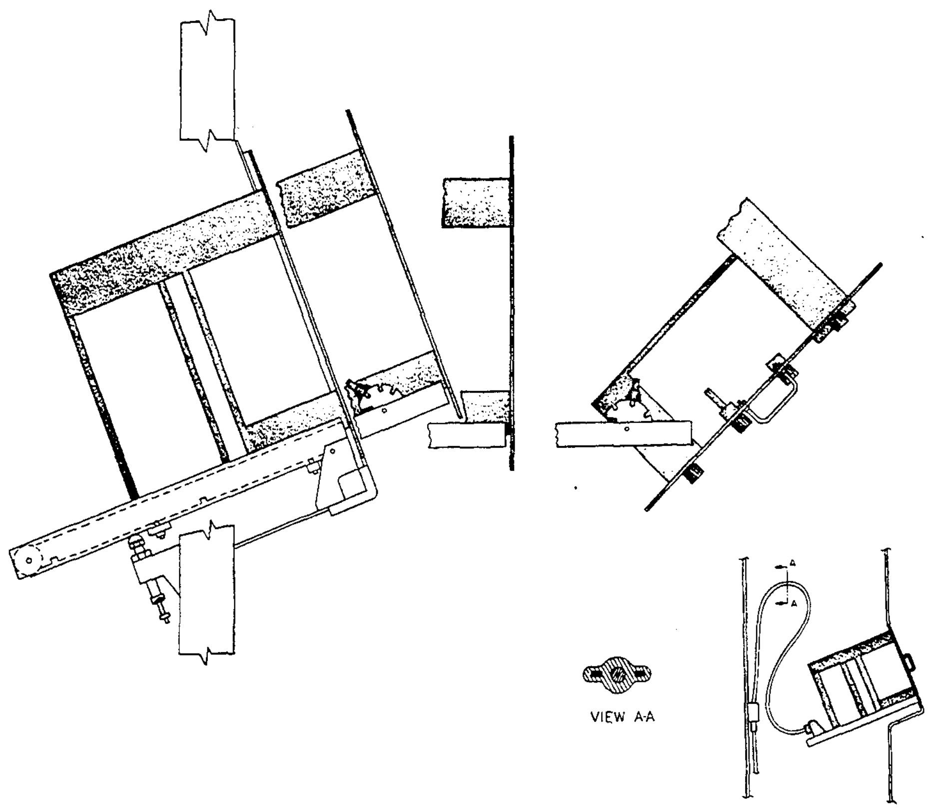


Fig. 3

Shock absorbers were provided at the end of the travel to prevent any damage to the chassis.

Behind the console, all chassis were slide-mounted, easily removable, and had one distinctive feature, a 10-ft "coil-cord" cable. The chassis could be removed from their tracks by loosening four thumbscrews, then placed on a bench or a table 5 to 10 ft away. This meant that the maintenance man could service the chassis while the console was operating, affording him the capability of instrumenting while in service. This feature proved invaluable in saving maintenance time. The coil-cord arrangement, shown in Fig. 4, was installed wherever possible throughout the console.

The operation and maintenance areas were divided by a section devoted to instrumentation. This section was designed to serve both the operator and the maintenance man. The instrumentation included an oscilloscope and a digital voltmeter. Because of the inaccessibility of the 30 critical voltages in the system, these instruments were partially automated. Frequency of measurement did not warrant a fully automatic system. Stepping switches provided the program for the selector switches mounted on the front panel. Three projection-type indicators

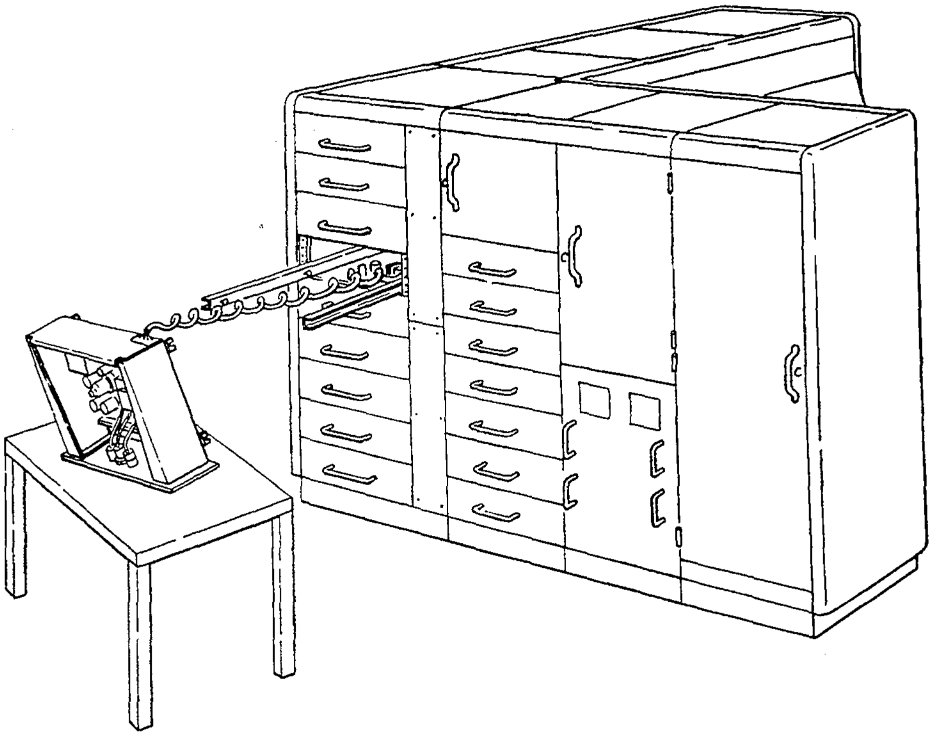


Fig. 4

provided readouts for the programmed voltages. These were positioned at eye level and represented the *actual* voltage being read in blue, the *standard* voltage (what should have been read) in white, and the *tolerance* for this voltage. Located on the same panel were more selector switches, color-coded and area-marked, to provide switching for the oscilloscope. Appropriate scope triggers were color-coded to correspond with the signal to be analyzed. Although the information displayed was from complicated sources in the equipment itself, the entire area was simplified so that performing these tasks became easy. This area also contained the main power switch. We chose to call this area the System Analyzer Panel (see Fig. 5).

The panel was hinged and, because of its trapezoidal shape, the manner of hinging also became a unique problem (see Fig. 5). We borrowed the design from an automobile trunk hinge. This served the purpose of swinging the panel at an angle away from the face of the console and yet provided room to allow the rear of the indicators to clear the opposite side of the opening. With the panel swung approximately 120° from its normal position, accessibility for maintenance was no problem.

The prime consideration for construction was the framework to be used.

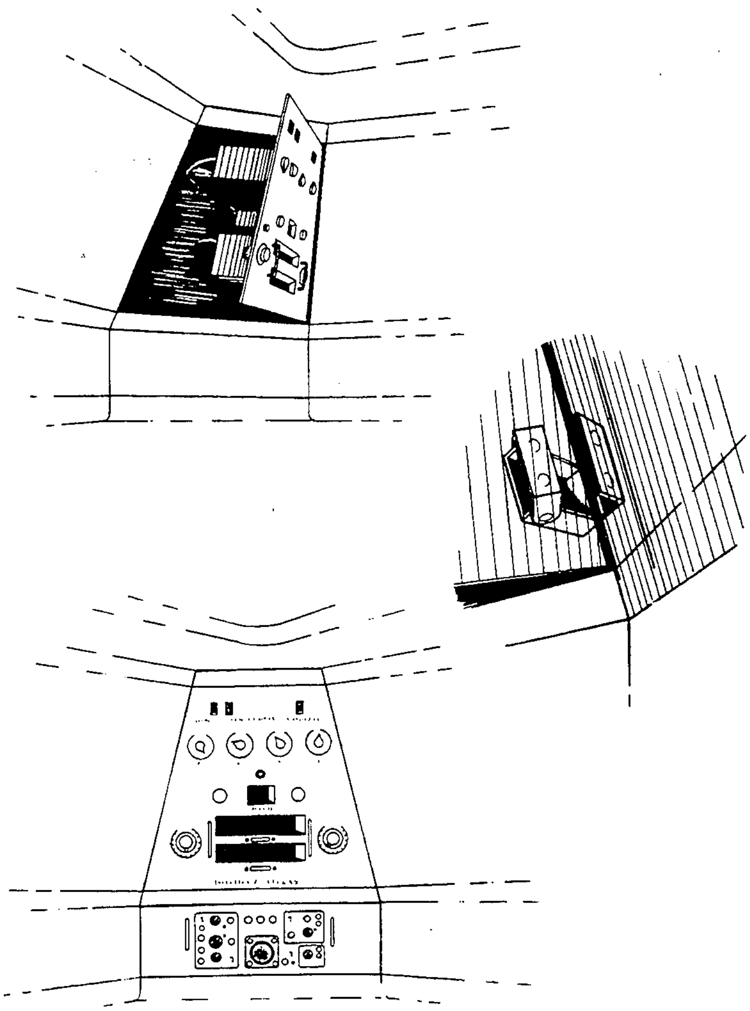


Fig. 5

This choice was not an easy one since a "custom appearance" was desired. Our investigation disclosed the following facts:

1. The frames should have ample free working area between frame members. We did not want side panel support members to dictate positioning of the equipment within the rack (see Fig. 6).
2. A "custom look" is only obtained with long sweeping lines; therefore, the frames should not have panel areas or outside lines broken into frame-width segments.
3. Several extra-wide chassis would require special cabinets. This could mean tremendous expense.
4. With all the panel area involved, the console would have to be designed

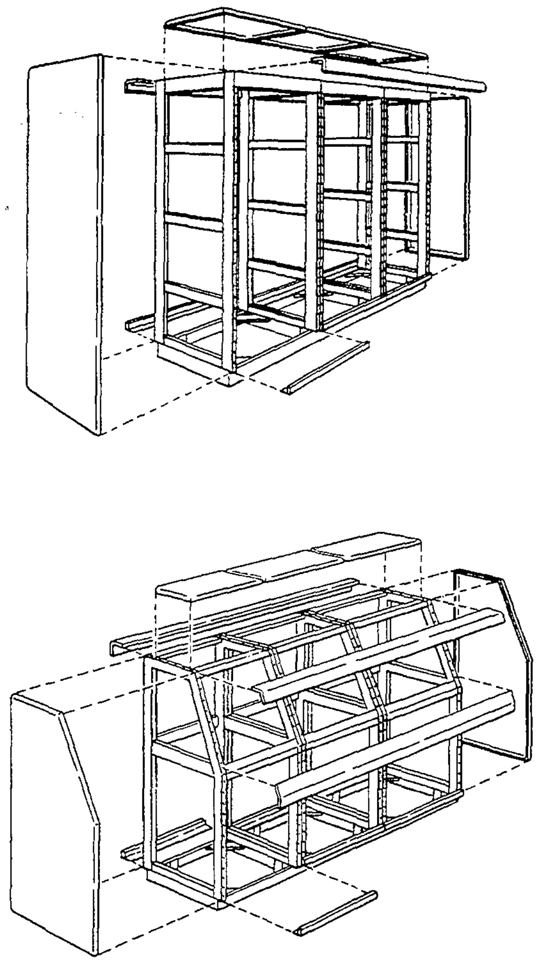


Fig. 6

with some curvature. Using pie sections to accomplish this would mean a terrible loss of valuable space and would also be expensive.

5. During construction we wished to work freely in and around all the framework without having to mask off finished surfaces that would show scratches and marks.
6. Painting would be a problem. Removing equipment to get the console painted would involve a lot of lost effort.
7. The console would have to be built in sections in the laboratory. The limiting size was the passageway through doors and hallways. We did not want to build a boat with a 10-ft beam in the cellar and then have to knock out the side of the house to get it out.
8. One existing unit, the digital-to-analog converter rack, was a sledge-hammer custom design and installation. If it was to be a part of the

console, it would need a gigantic face lifting. Besides being wider than the standard frame, it had an I-beam center construction that was welded to the back of the cabinet as shown in Fig. 7.

Fortunately, there was an "off-the-shelf" frame available (Fig. 7) that met all of our requirements. It met Military Specifications for strength and had a bonus feature—enlarging a frame would require very little effort.

With this type of frame, designing the console layout became a relatively easy matter. The panel layout dictated the chassis' placement in the console. Instead of using pie sections to provide the required curvature, we designed the trapezoidal panel to fit into the 90° corner of the console. The sweep of this panel helped to give the console the desired custom look because now there were virtually unbroken lines in the panel area. The sloped position of the panels was obtained by using standard long turrets. Fig. 7 shows how these were placed one panel width down from the top of the framework to provide room for chassis to be placed in the area above the turrets.

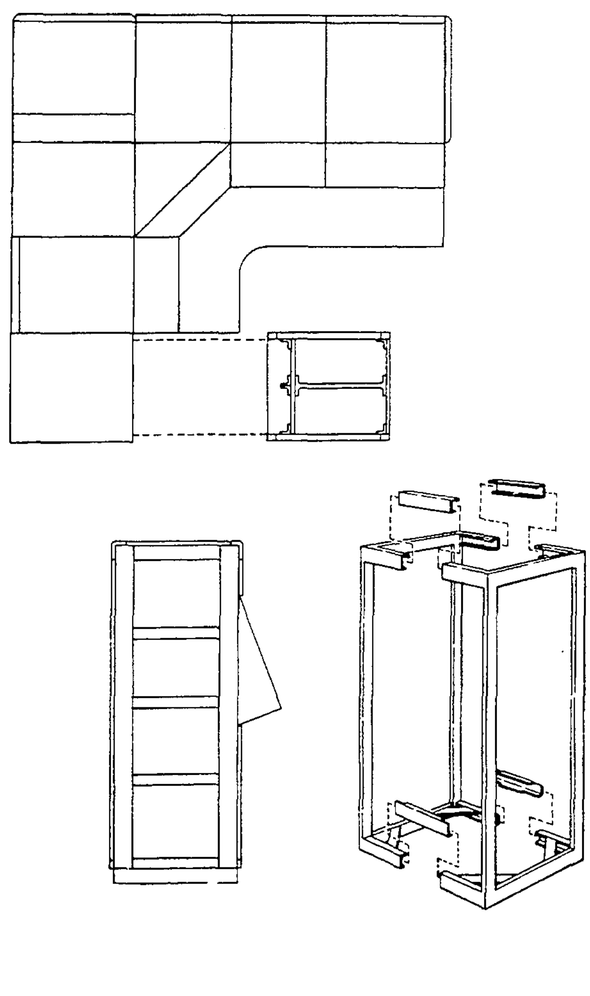


Fig. 7

We were able to lay out a 90° corner at the rear of the console. This space provided extra room inside the console for fans, cabling, etc. Expanding the frame was a simple matter of cutting four frame members, forming four extension pieces, and welding these to the frame members that were cut. Presto! We had an extra large frame for the cost of a couple of hours work, and in a couple of hours delivery. Being able to improvise in many ways with this framework made us feel as if we had a "Tinker Toy." Creativity was in full bloom! We felt we had something that we could do things with and, by George, we were doing it.

Building and mounting the counter for the operator was very simple. It was lined out on plywood, covered with formica, and bolted directly underneath the turrets. This was probably the most inexpensive counter that we had ever built, but it certainly served the purpose. The communications, cigarette lighters, and ashtrays were mounted underneath the counter, easily available to the operator.

The entire console was built in sections, as shown in Fig. 7. We had no worries about scratching finished trim or decorative panels because these surfaces were attached *after* the console had been completed and checked out.

Installation was accomplished with a minimum of effort, since the chassis had been modified one at a time during the console construction period. They were made available for modification as the system idle time permitted. One important maintenance aid resulted from this chassis substitution: We had purchased a "fat" power supply that could be inserted into the system in place of any of the supplies we were modifying. Eventually, this power supply became a part of the new equipment, which meant that the maintenance man, through patch networks in the system, could substitute the spare power supply for any disabled one.

Installation became a matter of rolling in the new frames, dismantling the old system, placing the chassis that were going to be used in their new homes, connecting the cables, checking out the various sections, and turning the equipment on the air. This effort took two weeks, and the equipment went "on the air" the first time the ON button was pushed. I have never performed an installation as quickly and neatly as that one.

After the console had been in operation for several months, the entire system had to be moved to a new building. Experience gained in the original installation resulted in a moving task that required only four days for complete removal and reinstallation. The ease with which the move was accomplished was attributed to the manner in which the console had been assembled. We could remove all the exterior finish surfaces with bolts and nuts and pack them gingerly into cartons, then take the sections apart as they had been built, through cabling, put casters on each section, and roll it out of the building. It was almost a pleasure to move this machine. There were no hampering factors of cutting wires, removing chassis, and all the usual fear of breaking components. They had all been well packaged and locked into place.

All our efforts toward building into this console simplicity as we knew it paid off in the end. Talking in terms of time, it really became dollars and cents. As for appearance, we were sure we had attained our "custom look" as is evident in Fig. 8. The console had its long sweeping lines. The curvature was not unreasonable to look at. The panels themselves had the appearance of simplicity. Operation and maintenance of the machine became a simple task. All this, plus the long cowls and paneling that went on after the machine had been built, set this particular design apart from any others that we had performed. The one "crucial" decision left to be made was "what color?" Most people in the industry at that time were finishing their equipment in greys, blacks, krinkles, and dull hammertones. Our machine had to be different. It, to us, had been pioneering effort in layout, design, construction and appearance; and it wasn't going to be spoiled by painting it just any old color. The decision became quite a struggle within the company. So we compromised and decided to paint it a grey that turned out to be the most beautiful *blue* you ever laid eyes on. The panels were finished with a hard satin nonglare surface, which accomplished several things. It prevented fingerprinting and smudges, and allowed the engraving, both color and text, to stand out for the operator and the maintenance people.

The room into which the machine was going was also refurbished, with spotlighting on the console panel in the various areas important to the operator. The two walls of the room opposite the console panel area were painted burnt orange. The walls parallel to the back of the console were painted a silver white. This color scheme gave the operator a comfortable-looking area in which to work, and provided a brighter area behind the console for the maintenance personnel.

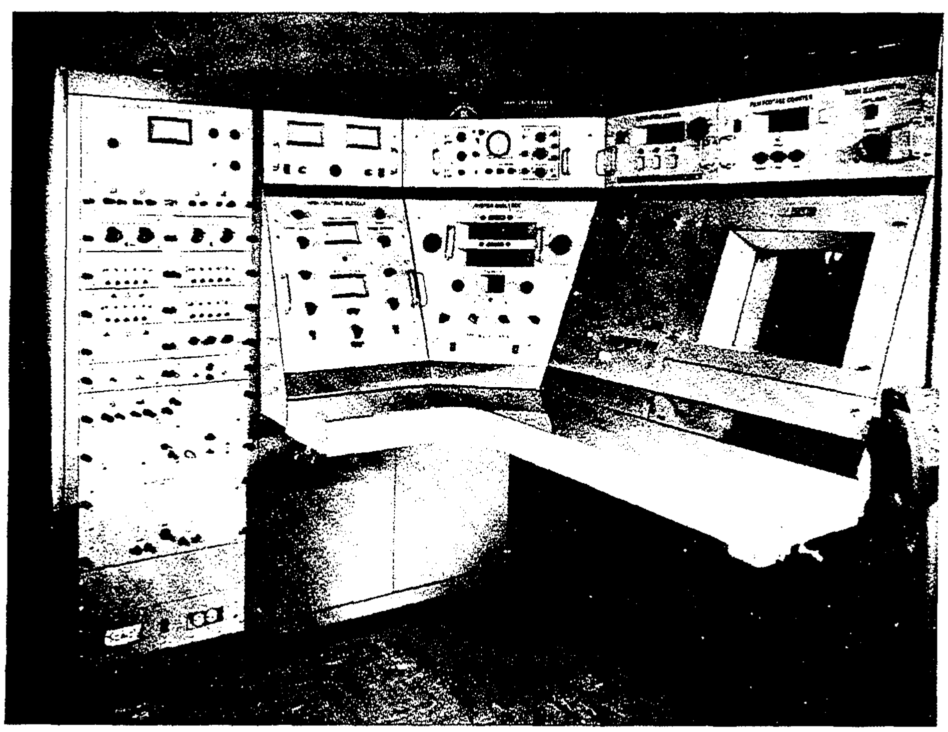


Fig. 8

The maintenance area was well lighted with provisions made in switching for lights to be on only when the maintenance man required them. This was accomplished with two 3-way switches located at either end of the room. The operator's chair was painted blue and highly chromed. The storage cabinet, filing cabinet, and desk were also blue. In fact, the word at the time was "Don't stand still in the room, you might get painted blue!"

There were some arguments about the color combination which were resolved by the room being closed until the "decoration" was finished. The end result was gratifying, drawing "Ohs and Ahs" from people who had been pessimistic at the time the designs were suggested and colors chosen. At the Grand Opening, this facility was established as the "place to see" at SDC.

Many unusual features are incorporated in this facility, including the automatic instrumentation, the lighting system with the dimmer and multiple intensities, safe lights, and the coloring of the room itself, which is set off with two large aerial color photos of SDC. The one feature that appeals to most visitors is the System Analyzer, which is the panel containing the three windows and the automatic switching. With the selector switches properly positioned, the equipment will function correctly. If both switches are programmed to read TWO separate voltages, the indicator lights for the numerical readouts will go out. In the tolerance window will appear the word "ERROR," in red. This tells the operator or maintenance man that he has programmed an incorrect selection. Should the operator still insist that the machine probe out the TWO separate voltages simultaneously, the indicator will call him an "IDIOT." Under normal circumstances, he will forget the whole thing and start over again. If he should lose his temper, and push the button again, and demand an indication, it has several more unkind words to tell him. This was a simple feature to put in the machine, but has become most effective in telling operators how to use the System Analyzer equipment correctly.

At first, most people feel rather hurt that a stupid machine will sort of talk back to them. On reflection, they realize that the machine is only automatic insofar as it is told what to do.

As you can see, we tried to promote our philosophy "To satisfy, simplify" throughout this project. We by no means accomplished the task perfectly, but we feel that we progressed a long way in the radical designing of electronic enclosures. This background became useful to us many times over in projects that we have worked on since then, especially in building new equipment such as the console shown in Fig. 9. This console was designed to control the input/output relationship of a Philco 2000 Computer and our large System Simulation Research Laboratory (SSRL). It really is a complex transducer control console. All the techniques that had been learned in repackaging the Tape-to-Cathode Ray Tube Facility were applied to the design of this equipment. The console was to be low in profile and used as a control center for other elaborate equipment located throughout the Laboratory. A parallel function was to control the input and output information to the Philco 2000 Computer. It would be supported electronically by fourteen 6-ft racks located in the same room. Its appearance had to be something different, though inexpensive. Once again the stipulation, "Custom

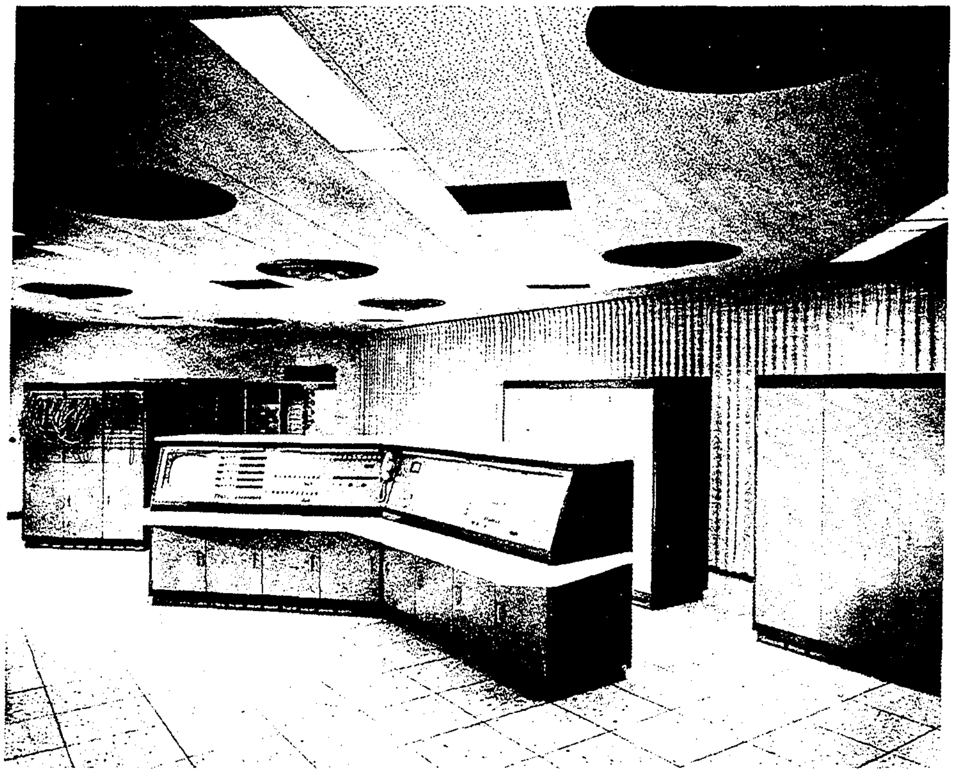


Fig. 9

look at standard prices." We applied the same techniques that we had used in repackaging the Tape-to-Cathode Ray Tube machine to this console. Construction utilized slope-front paneling, but instead of turrets, we used slope-front frames. Although one pie section was used at the center of the console, designed curvature made it possible to utilize this space to contain part of the equipment. Packaged within the console were two 5000-terminal patchboards with their appropriate cabling, some three-hundred 50-pin connectors, automatic power supply sequencing and switching, meter indication for all power supplies at the push of a button, and communication facilities to all the outside world, including the laboratories. In fact, because of the remote areas that it would control, closed-circuit television was incorporated in the left side of the console. The right side of the console contained the "Bit Information" display, in or out of the computer, in the form of brightly colored indicators.

Designing the "custom look" into this console employed a rather unique idea. We wanted the console to look streamlined, have long unbroken lines, and also give it the appearance of something moving. If you were to look down on an old-fashioned biplane, the wing outline would give the appearance of movement. This outline was the basis of the console's design (Fig. 10).

The design was executed inexpensively, and we were able to use standard frames. The "dress" which set the console off was the counter top and the table top. These both were laid out and cut from plywood, then covered with formica.

To sell this idea took more than a perspective drawing on paper. People just didn't "see" the dynamic movement in the design, so a model was built to scale. The design was bought immediately. We learned another lesson: Make a scale model to show your creation to other people who just might not understand your way of thinking.

Because this system might have to grow to four times its original size, provision had to be designed into the console for expansion. This brought about a novel panel design. The panels in the console are made up in two layers as shown in Fig. 11. The first layer or back side is what might be called the framework, or base, for the finished panel. All switch layouts, meter holes, and component mountings are breadboarded on this panel. When the machine has been checked out, and accepted as a working piece of equipment, the final position of all switches, meters, plug arrangements, etc., is detailed into the design layout of the front, or finish, panel that is exposed to view.

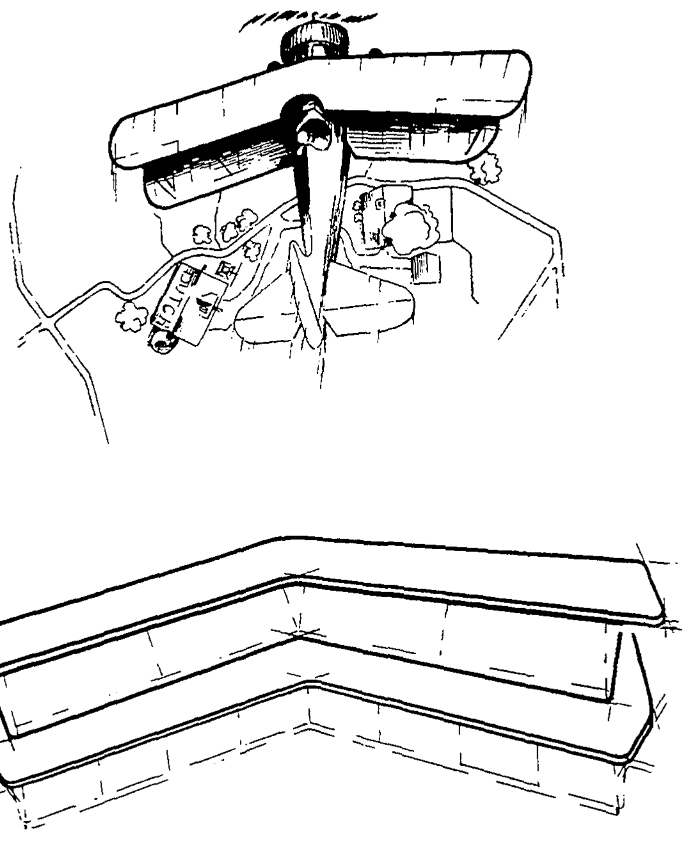


Fig. 10

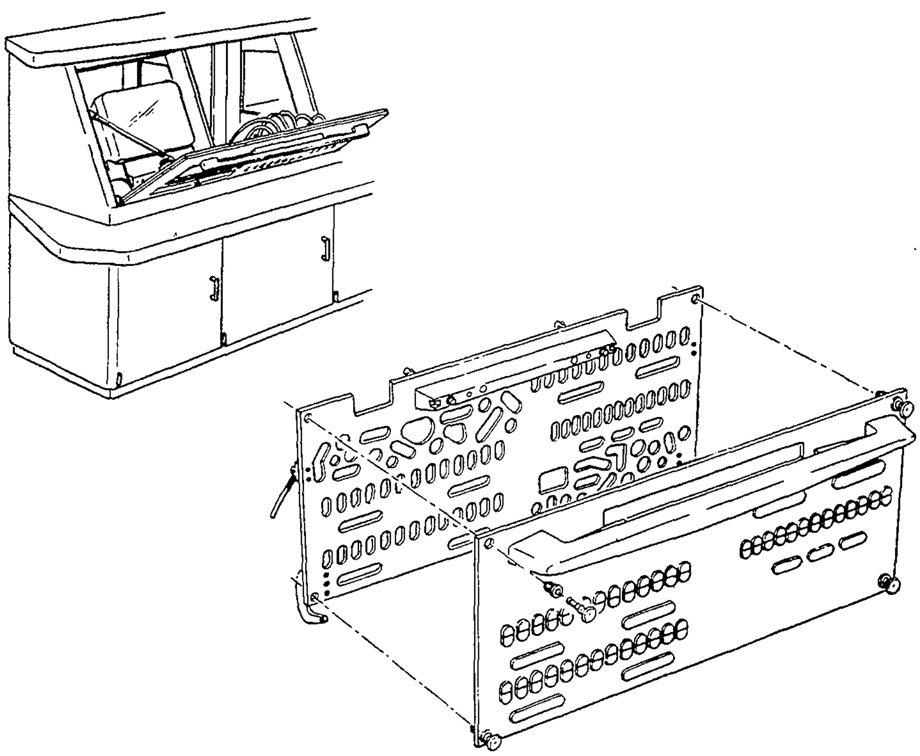


Fig. 11

This approach brought two things. When we were ready to put on the finish panels, we knew the equipment would be right. When expansion time came, we could experiment with the expansion design to our heart's content, drilling all kinds of holes in the bottom panels and not having to worry about marring the finish panel surfaces. We are very proud of this console. And it works too!

The long, sweeping line effect, attained at very little expense through use of multiple-width panels, was pleasing to the eye. Now this console too has become an SDC showpiece.

CONCLUSION

Thus far I have described past examples of creativity in package designing. But perhaps you, like me, are dreaming about the next console "we" are going to build; and we are wondering just how, and in what form our creativity will take shape. We have no idea of why the equipment will be built, and at the moment, we don't care.

We, as Package Design Engineers, "see" a pleasing family of sweeping lines and curves. The view of an approaching monorail train might be just the effect we are after. Let us sketch it out, as in Fig. 12, and see what it looks like when applied to our console design. That could be it! If we use a little chrome, some brushed and anodized aluminum, and plexiglas on the one end, and finish it off with wood, we can give this console that distinctive custom look that we are striving for. Perhaps, this time, instead of formica-covered plywood for the top and counter, we can use an oiled-walnut finish. Now that we have the look we wanted, let us investigate how our philosophy "To satisfy, simplify" fits with this design.

The operator can be well thought of in this design. We could designate the entire front side of the machine as his working area. The controls and indicators can be arranged so that his movements will require a minimum of effort. We will place them in a top-to-bottom, left-to-right sequence established by the operation of the equipment. All controls will be within easy reach from a sitting position. All indicators will be at eye level. This arrangement, though phantom in this early stage of the design, can easily be shuffled later to meet the requirements for the operator's comfort. Obviously the oiled-walnut writing surface is for his convenience also. Appropriate communication and other work relief facilities (cigarette lighters, ash trays, etc.) can be dispersed throughout the area, but positioned at the well-used portions of the console itself.

We can make provisions for maintenance at the end of the console. The 180° plexiglas contour can enclose indicators, check points, level adjustments and

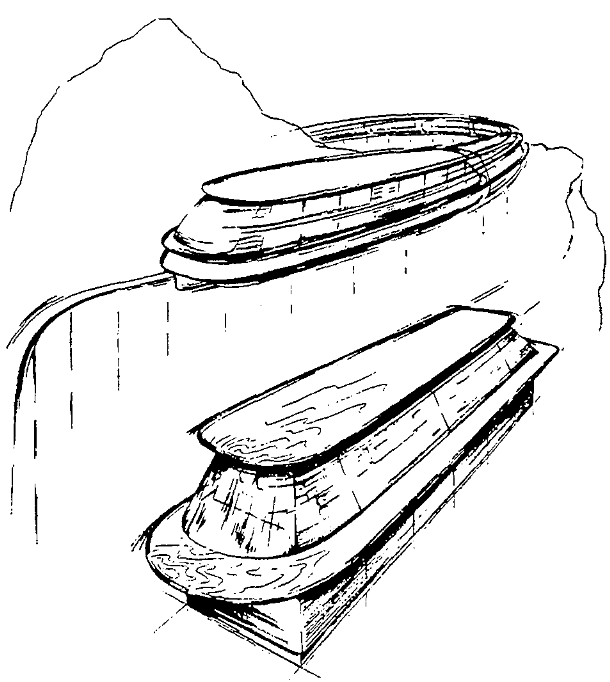


Fig. 12

any other equipment that the maintenance man may require. The plexiglas enclosure can be a door that provides accessibility only upon demand of the maintenance personnel. By positioning the maintenance man well outside the confines of the operator's area, we have provided him with maintenance capabilities while the machine is in operation. We have also given him ample desk area to work on with the wrap-around writing surface.

Even a critical look will reveal there will be no hardship in the construction. Our design is based on standard framework. The custom trim, stemming from our creativity using a free hand, really sets the console off as different. Other designers will look at it and swear it's "custom gear." As for packaging the equipment into the console, we'll find there will be very few problems because we will be using standard, "off-the-shelf" frames. These will not interfere with packaging density within the framework and also will allow us a great amount of freedom to exercise our creativity for obtaining that "custom look." We will have accomplished all this at relatively low expense.

A closer look will show that we can build this console in sections. Sectional construction means that intrarack cabling will not be complex, moving the finished gear to its permanent location will be a simple job; checking out the equipment before installation will present no problems; and final assembly can be accomplished in a short time. Here is the biggest bonus of all—we know that expansion for future installations will present minimum requirements. Conceivably, expansion units could be "tag along" appendices on the flat end of our initial design.

At present, we have to be vague about the color scheme; but when the time comes, we will choose our colors to "fit" the atmosphere into which the console is going. The work that it is to do will contribute to the choosing. The people who are going to use the console, and practically live with it, will also have an input. We, as designers, must have regard and respect for all of these influences. The operators and maintenance people should enjoy working in the area. Observers should be pleased with the operation and appearance of the equipment. Over the long run, this means expense—*low* expense. We will have accomplished something to be proud of.

There is one last thing we must remember to do. When the project has been assigned to us, and we recognize that our design will fill the bill, we will sell our idea with a scale model. It will give depth and feeling to our design, which is often hard to transmit to others, even though it is portrayed with a realistic and accurate perspective drawing. We are deviating from the standard, and people are rather slow to accept new ideas.

We cannot force their acceptance of our ideas, but a model that exemplifies our philosophy "To satisfy, simplify" will go a long way toward having them agree that they see the concept as we do—a dynamically distinctive design, the heart of a pleasing finished product which, when built, will serve its masters well.

DISCUSSION

Q. (Hank Cohen, Interstate Electronics, Anaheim, Calif.) I agree with some of the points you made that a few manufacturers are not using ingenuity in bringing about good products, and we should point this out to them, but the one thing I abhor is every product coming out of a company looking different and appearing as though overall package design was of primary importance, that creativity on the part of the designer was the first goal. As you can see, I just disagree entirely with what you are saying.

Q. (Al Painter, Bendix Computer, Los Angeles, Calif.) Are you asking us to consider the whole package design as a homogeneous unit and all parts to be considered the same, or are you asking us to abandon the conventional lines and adopt your lines wherein we would have the opportunity to glue pieces of trim on the outside?

A. Let me answer that with a couple of questions, if I may. Do you use large packaging? I am speaking of 8-, 10-, 20-ft long packages, 3, 4, 5, 6 ft high. Do you like to design within the 19-in. panel configuration that is common with the majority of the consoles on the market today? Do you feel you have to confine yourself to 19-in. panel restrictions in your design wherein this is the final appearance of your equipment? Have you ever done this?

Q. No. We are in a slightly different line. We cannot package tape decks and printers in 19-in. panels, so we never use any of the conventional lines.

A. That is my point exactly, but what do you build this equipment around? Don't you build it around a basic frame?

Q. No. We consider the package as a homogeneous part of the whole unit, in other words as a functional part. Each part is designed separately with the tape deck, the printer, and the brain in mind.

A. Individual pieces of gear. These are the people I am talking to.

Q. (Leon Williams, Lockheed Missiles and Space Div., Computer Dept., Palo Alto, Calif.) I might just mention that I am in the packaging of large computer and data processing systems, and we have many times gone through the problems which you are mentioning and discussing, and after attempting, at great cost, to develop the types of cabinets and the packaging methods you speak of, we finally worked in conjunction with a firm in Los Angeles and now there is available on the market exactly what you are speaking of—heavy-duty structural systems, with an extruded structural-member framework, in which you can get the cabinets any size, any width, any depth, any height, any configuration you may want, with the side panels etc., not being structural members, and with any individual manufacturer's framework or bezels, trim, motif, or whatever you wish to call it. This is now available and on the market and it is known as Basic Packages or Basic Cabinets.

A. Thank you very much; I haven't heard of them. In fact, I am in L.A. and will investigate.

Q. (Ronald Sarnie, Baird-Atomic, Waltham, Mass.) I agree with you in one sense and I do believe in individuality in design, but having participated in a lot of programs where I have been stuck with a standard 19-in. rack or 24-in. rack, I have found that the biggest challenge (and I told myself that I was never going to use that word again when anyone ever told me that a job was a challenge), but the biggest challenge that I did find was trying to package around these 19-in. limits. I found that right there is where the real thinking and design problems come into play. I found that it was there that I was able to use many different types of methods for packaging. I do agree with you that some of the manufacturers should perhaps give us some more widths (they do have a 24-in. width now and they are improving). But it would cost a fantastic amount of money to use all of this individualism in a console. I may be wrong—you may have some cost figures that could disprove this; if you do, I would like to talk to you about them.

A. I would be more than happy to. Let me enlighten this cost for two minutes. If you look in the paper you will see two consoles, one is maybe a half-million dollars worth of equipment and the other is four-hundred-thousand dollars worth of equipment. They are well within one-hundred-thousand dollars of each other. The cabinetry that they have been put into is better than 40% less than if you had bought a custom cabinet on the market today. The tops and the sides are ordinary plywood with formica covers. The tape-to-CRT machine uses standard panels. There is nothing custom in it, but it looks like a custom console and there is only one bit of individual design in that console: the strips between the panels are missing. That is the key to that design. You will also find that in the other console, it's key to good looks, and I really think it is good looking, is that it has multiple-width panels and these are standard. I am not talking expensive custom cabinets to work with, I am talking common sense; "simplify it."

Q. What you are saying is that the type of equipment that does not have to get off the ground does not need the heavy framework. On this I agree with you. I think some of these frames are far too heavy for sitting around in a little operational room somewhere or on a production floor being utilized for test equipment.

A. You are beginning to think as I do.

Q. (Archie Yergen, Tektronix, Beaverton, Ore.) In getting down to details, I wondered if this equipment had to meet any environment specs? If so, how you found a coilcord that could stand the high and low temperature?

A. It didn't have to meet any environment except four people who operate it—and that is a pretty difficult environment.

Q. (L. V. Larsen, General Electric, Coshocton, Ohio) Apparently your approach to custom design of these things is going to involve some rather lightweight construction. You spoke of plywood covered with formica. I would like to ask you how this reconciles itself with the current homing in of the National Fire Protection Association and the Underwriters Laboratory in their campaign toward making computer assemblies particularly fire resistant?

A. You will find that you can get plywood impregnated with fire resistant material that you can't burn it with a torch. That is the one we use and it doesn't cost that much more.

Q. (Art Kato, Minnesota Mining, L. A., Calif.) With your new type of concept, what happens to our existing systems like in JPL or Wright-Patterson where they have a complete system? Do we go back and obsolete them?

A. No. But I think you are going to find that in most of these ground control equipment centers, they are going to the multiple panel width. If you will notice in some of the trade journals and some of the space magazines, etc., the block houses that are five and six years old have 19-in. panels and they look very cumbersome. But, take a look at the new ones that are going into those installations, they are multiple width with longer slope fronts on them. They are an entirely different architecture. They are leaning toward this type of construction. You don't have to revolutionize the world—just let the cabinet manufacturers know what you want.

Q. (Howard Roberts, Hewlett-Packard, Palo Alto, Calif.) I think you will find that many systems designers buy certain pieces of equipment, as your installation bought a certain unnamed oscilloscope. If you had decided on a 16-in. rack panel as being nice for your installation, where in the world would you have gotten a 16-in. wide oscilloscope.

A. We made the package to fit the instrumentation that was available. We do not build a package and then go out and buy the instruments.

Q. That is why I think you will find that most instrument manufacturers offer 19-in. wide options in their packages.

A. That is right, but if they would put a false escutcheon or facade on some of their instruments, you could put these instruments in any console and it does not have to be confined to 19 in.

Q. (Al Acken, RCA, Van Nuys, Calif.) At RCA we have a need for two types of packages, one of them is a standardized package (19 in.) and for this we designed an RCA standard cabinet and this accepts the power supplies, etc., that are on 19-in. widths. On the other hand, when we have a custom design, the design is not dictated by the designer but by our human-factors group and stylists and then the designer is left to design a console to fit within the limits that he is given. I don't know whether your particular system will help us or not.

A. Well, let me say this much, I feel for you. We have in our building something like 600 human-factors people who are more than willing to help us in the engineering department on any console that we are intending to build, but their restrictions to us are not really size limitations. A funny thing happened recently. There was an inspection in Washington of a facility and it was written up in *Time.* The comment was that it was beautiful equipment, humanly engineered for a person with four hands. I have been down the path with these people and I think that they should talk to the engineer while they are designing. They should consider it a community effort, rather than impose these specifications on them.

Q. (T. Tinkler, Minneapolis-Honeywell, Seattle, Wash.) I think we have been in the same boat you were talking about, Vince. There are some installations where the commercially available rack and panel mounts are excellent, there is no question. In a blockhouse installation you would have a terrible time selling them on a style console. Consider the office furniture manufacturing people when you go into one of these style consoles; these people are ready and willing to work with you and you will come up with a beautiful design, a real rounded corner proposition, and I think your airplane swept-wing thing here carries this out. We had the same proposition on an installation in Washington, D.C., and it worked out beautifully.

A. Thank you.

Q. (Wayne Franklin, Lockheed Missiles and Space, Sunnyvale, Calif.) How does the use of plywood with formica covering lend itself to RFI (Radio Frequency Interference) shielding capability?

A. I am not packaging in that kind of an environment with that particular material. I am speaking of individual packages where the appearance or the atmosphere of the area that it is going into is important. It is not necessarily an extreme environmental function that it has to be built to.

Flexibility in Control/Display Panel Packaging

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This paper describes a design program to achieve flexible and pleasing control/display panel packaging for the Ballistic Missile Early Warning System at Thule, Greenland. The object is to provide an optimum combination of initial cost, cost to change, and packing factor in the equipment consoles.

CONTROL/DISPLAY equipment required to couple operators to large electronic systems now represents a significant portion of total system cost and complexity. Two control/display equipments which illustrate this point are shown in Figs. 1 and 2.

Fig. 1, the system control and switching console used at the Thule, Greenland, site of the *Ballistic Missile Early Warning System* (BMEWS), is an example of a very complex piece of equipment which is designed to be viewed and operated by one operator. In the 20-in. by 64-in. panel area of this console approximately 1000 different indications are displayed. This is almost one indication per square inch. In addition, controls are provided to allow virtually complete flexibility in interconnecting the various system elements throughout the site in order to optimize system performance.

The equipment status panel, also used at the Thule BMEWS site, is

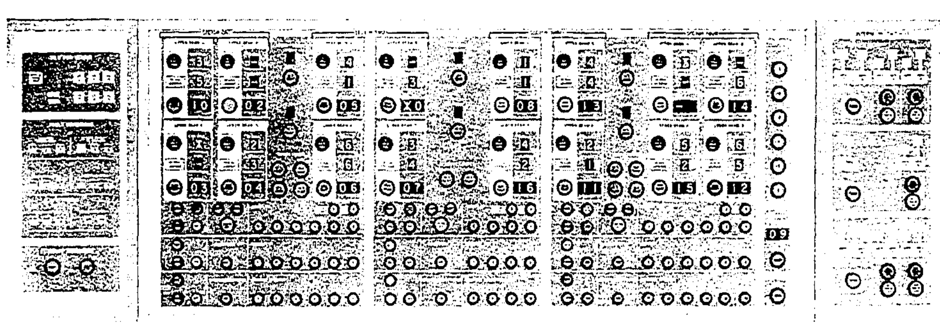

Fig. 1. BMEWS system control and switching console.

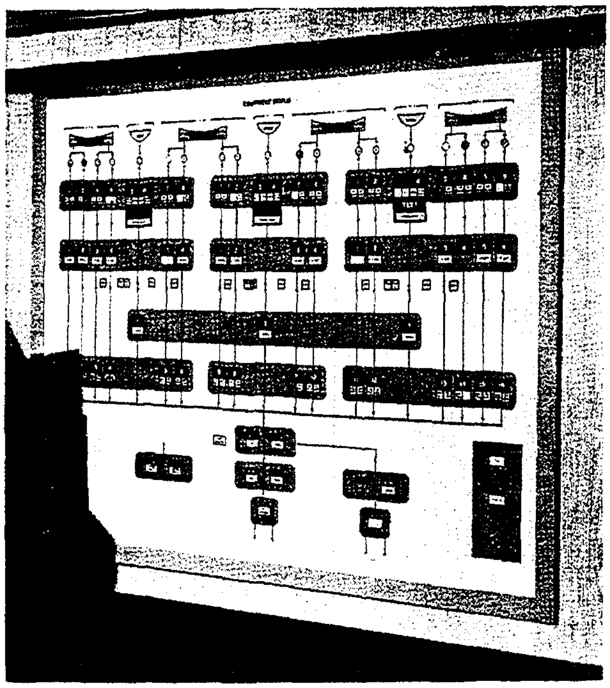

Fig. 2. BMEWS equipment status panel (original version).

representative of the very large wall-mounted displays used to convey information simultaneously to a number of operators. It is approximately 6 by 8 ft in size. The panel shown in Fig. 2 displays slightly over 700 different indications.

It seems almost inevitable that control/display panels require changes after they are built, and often after they are installed and operating. The primary reason for this seems to be the "crash" nature of most military and government programs.

During the relatively long cycle from the development of the first system concept to the definition of a final system configuration, changes are very likely to occur for a number of reasons. System changes will likely be made to take advantage of advances in the state of the art. Many times the customer's requirements will be changed, causing system changes. Finally, funding considerations often call for system changes.

In addition to these unpredictable changes, often changes are brought about by incremental implementation of a system. While it is possible to predict that incremental additions will be made, it is not possible to predict the exact form the additions will take. A control/display configuration cannot be provided for the system additions until the additions are more exactly defined.

In order to meet schedules on a "crash" program, it is necessary to begin the design, and sometimes even the fabrication, of control/display equipment before a system design is complete. When changes are made in system design then changes must also be made in the control/display equipment.

Extensive modifications made to the equipment status panel will serve to illustrate the extent and nature of changes frequently required because of system design changes, during and after implementation. Although Fig. 2 actually pictures a full-scale mock-up rather than real hardware, the first real hardware panel built, delivered, and installed at the site was identical to this mock-up. Fig. 3 shows this panel as it exists now at the site. A large number of indications have been added over the original version, and indicators have been shifted in position to make room for the new indications. The present version displays almost 1300 indications, rather than the 700 displayed by the original panel. Fig. 4 shows the present panel with the overlay removed. Display components are mounted on the three subpanels shown. Modification of this panel required that the 6- by 8-ft overlay and three component mounting subpanels be scrapped and replaced. Scrapping of the component mounting subpanels and replacing them with new subpanels required not only the mounting and wiring of many new indicators, but the unmounting and remounting of all the existing indicators and the rewiring of many of them because of the shift in location. Virtually all that could be reused of the original panel were the frame and dust cover. Many of the other BMEWS control/display equipments required modifications ranging from very extensive to minor. However, the equipment status panel, since it displayed the status of every major system component at the site, was most modified, and was most expensive to modify. It was our experience with this panel which convinced us that a technique which allowed changes to be made easily and inexpensively needed to be developed.

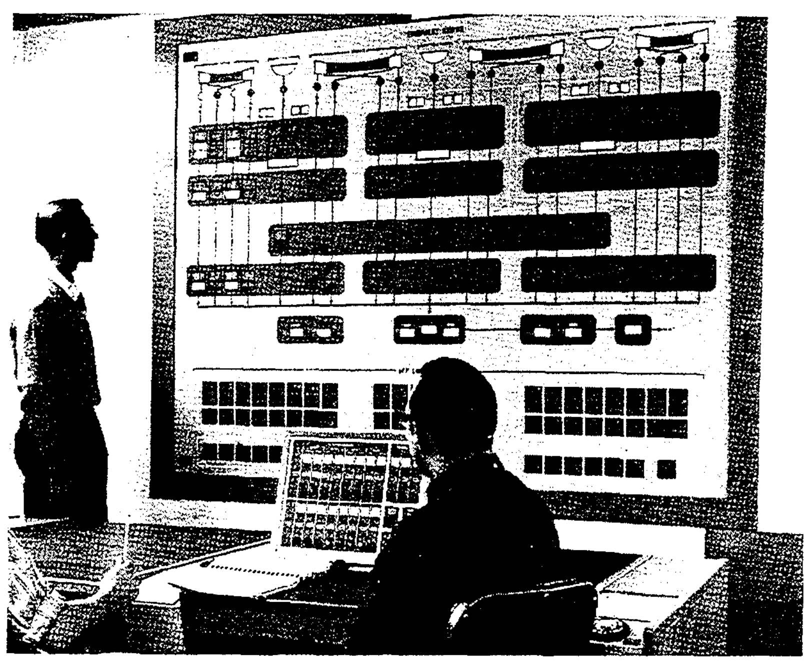

Fig. 3. BMEWS equipment status panel (present version).

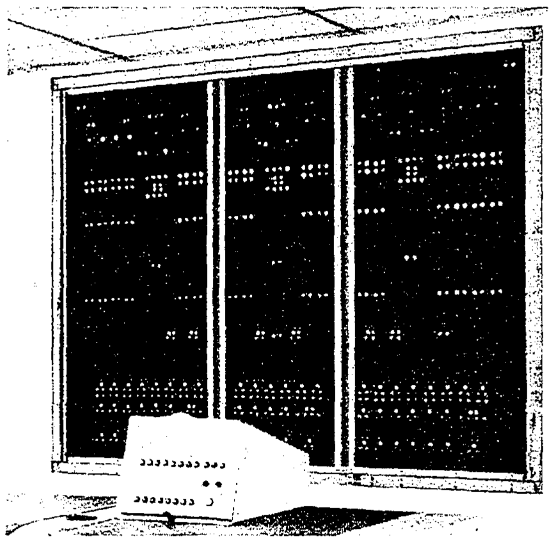

Fig. 4. BMEWS equipment status panel (dress panel removed).

The first step in attempting to come up with a new panel technique which would allow fast inexpensive changes to be made was the cataloging of general requirements control/display panels should satisfy. These requirements fall into two general categories: human-factors considerations and mechanical considerations.

One of the most important, and most often unsatisfied human-factors requirements is that panels be easy to maintain. This requires at least that components with low reliability (for example, incandescent lamps) be replaceable from the front of the equipment, without the use of tools of any sort. There are many recorded instances of serious degradation of control/display equipment performance brought about by failure of operators to change failed lamps because lamp replacement was made too difficult. It is also highly desirable to allow easy access to other components (switches, relays, etc.) and wiring; however, since the nature of these components generally requires that some tools be used to repair or replace them, and since they require little attention, it is not as important that they be accessible without the use of some common tools.

A second requirement is that as nearly as possible, complete flexibility in choice of indicator size and shape be allowed. This requirement means more than simply modularization of indicator components. To satisfy the varied conditions under which control/display panels are used, it is necessary that indicators be available in any size, from $\frac{1}{4}$-in. by $\frac{1}{2}$-in. indicators on crowded console panels to very large indicators viewed from distances of 100 ft or more. For complex control/display panels to be as understandable and usable as possible, it is desirable that available indicator shapes include not only rectilinear and circular shapes, but also shapes representative of valves, antennas, missiles, flow lines, or any other shapes. In addition, there should be as few restrictions on spacing as possible. Use of a modular grid system for example may be too restrictive unless the grid size is significantly smaller than the smallest indicator size. A 1- by 1-in. grid used on a console panel would, for example, be too restrictive. Use of a 0.1- by 0.1-in. grid, on the other hand, would not.

A satisfactory control/display panel should be capable of accepting components of virtually every type. These types include:

Switches—Pushbutton and rotary
Indicators—Single color, multicolor, alpha-numeric
Rotary Components—Potentiometers, servos, encoders
Meters
Cathode ray tubes

Finally, to be satisfactory from the human-factors standpoint a control/display panel should present a pleasing appearance: an appearance that is satisfying to the operator and tends to build in him pride in his equipment.

Mechanical requirements, in general, are spelled out by the specifications imposed on the equipment. These may require the equipment to operate in varying degrees of shock, vibration, humidity, and temperature extremes. In addition control/display panels must withstand scratching and abrasion. In some cases it is necessary that they withstand salt-water spray or even immersion. In all cases they should be at least "drip-proof" to guard against inadvertent spilling of liquids (for example, coffee) on the equipment.

The second step taken was to examine the changes which had been made in BMEWS control/display panels in order to determine the general nature and extent of these changes. Many of the changes were quite minor. They involved only changing the titles or controls or indicators. Other changes involved the addition or deletion of controls or indicators.

In virtually every case requiring the addition of controls or indicators, the additional controls and indicators were so intimately related to existing controls and indicators that their placement became critical. That is, they could not simply be added to the bottom or side of a panel without being illogically placed and complicating the use of the panel. In order to ensure good panel design, it was necessary to add the required controls or indicators in such a way that they fit logically into the panel sequence of operation. This often required moving many existing components in order to install the new components.

It has been our practice to group controls and indicators in functional areas, as shown by Fig. 2. These functional groupings are arrived at in a number of ways. Controls and indicators may be grouped according to sequence of use or according to subsystem or, in some cases, according to equipment type. Such grouping is common and is in accord with good human-factors engineering practice. In nearly every case changes brought about by additions or deletions of controls and indicators were confined to one or a few functional areas on any panel.

A survey of the most common types of control/display panels was made in order to determine, first, how well they satisfied the general requirements defined during the first step in this effort, and, second, how easy they are to change. Three techniques were surveyed: single structural panel, edge-lighted panel, and double panel. All of these techniques are capable of meeting the mechanical requirements of most applications. That is, all can and have passed tests indicating they will survive and operate properly under the most severe conditions generally imposed by specifications. The techniques varied considerably in degree to which they satisfied the four general human-factors requirements, maintainability, marking flexibility acceptance of components, and appearance. None of the techniques provided good flexibility for accepting all types of changes easily and inexpensively.

The oldest and perhaps still most common technique is the use of a single structural panel (usually metal) which mounts all control/display components and is marked with necessary titling and other symbolography. The maintainability of this type of panel varies from poor to good depending upon the control/indicator components used. There have been round "bull's-eye" type of indicators, which offered satisfactory lamp maintainability for some time. More recently, "legend light" types of indicators and lighted pushbuttons, which allow satisfactory lamp maintenance, have become available. If care is taken to use only these control/indicator components or others which do not require lamp maintenance, the maintainability of this type of panel can be good, otherwise it is likely to be poor. The marking flexibility of this type panel is poor. There is a severe restriction on indicator sizes and shapes available. A single structural panel will accept nearly any type of control/display component. The appearance of this type panel can be fairly good, if care is taken not to expose all the mounting hardware required to mount the components used. Covering of mounting hardware can, however, increase the cost of the panel considerably. Those changes which involve only the retitling of controls or indicators can generally be easily accomplished, if the panel marking is done in such a way as to be removable (painted instead of engraved).

Edge-lighted panels which use front serviced lighting fixtures to mount lamps and use only lighted pushbuttons which are front-serviced allow for good lamp maintenance. Marking flexibility of edge-lighted panels is fair. They allow easy illumination of titles and single color indicators. Selective illumination of indicators, however (lighting an indicator while leaving adjacent indicators off) is difficult. Components which must penetrate an edge-lighted panel (rotary controls, meters, etc.) are complicated to handle. They require a separate mounting panel which is accurately registered with the edge-lighted panel. They also require that extra care be taken in the placement of the lighting fixtures to ensure that penetrations do not interfere with the distribution of light throughout the panel. The appearance of edge-lighted panels is often poor. The lighting fixtures protrude through the panel, overcomplicating its appearance. Edge-lighted panels are very difficult to change because of the critical placement of lighting fixtures required to ensure even illumination throughout the panel.

Double-panel construction was developed by the RCA Moorestown human-factors engineering group for the Atlas launch control and check-out equipment. It was developed specifically to satisfy the requirements for maintainability and marking flexibility. Typical double-panel configuration is illustrated by Figs. 5 and 6. Fig. 5 shows the front, or dress, panel with a wide variety of indicator shapes used to represent valves, tanks, flow lines, and rocket engines. Fig. 6 shows the unit with the front panel hinged-up exposing the component mounting subpanel. All components which require lamp maintenance are mounted in bayonet fixtures. Thus replacement of lamps requires only raising the front panel and removing and replacing an indicator module. No tools of any sort are necessary.

This double-panel configuration uses a dress panel of translucent fiberglass-reinforced plastic with aluminum egg-crate light baffles, and a separate component mounting panel. This design allows any indicator size and shape that can be marked on the dress panel and enclosed by aluminum light baffles to be used. Exactly the same indicator components are used for all indicators. Fig. 7 pictures a console panel which is part of an Atlas launch control complex. Three wall-mounted status panels, which are also part of an Atlas launch control complex, are shown in Fig. 8. The same indicator components are used for both the small console indicators and the large status panel indicators.

There are now techniques for handling most types of control/display devices with double-panel construction. However, double-panel construction works best

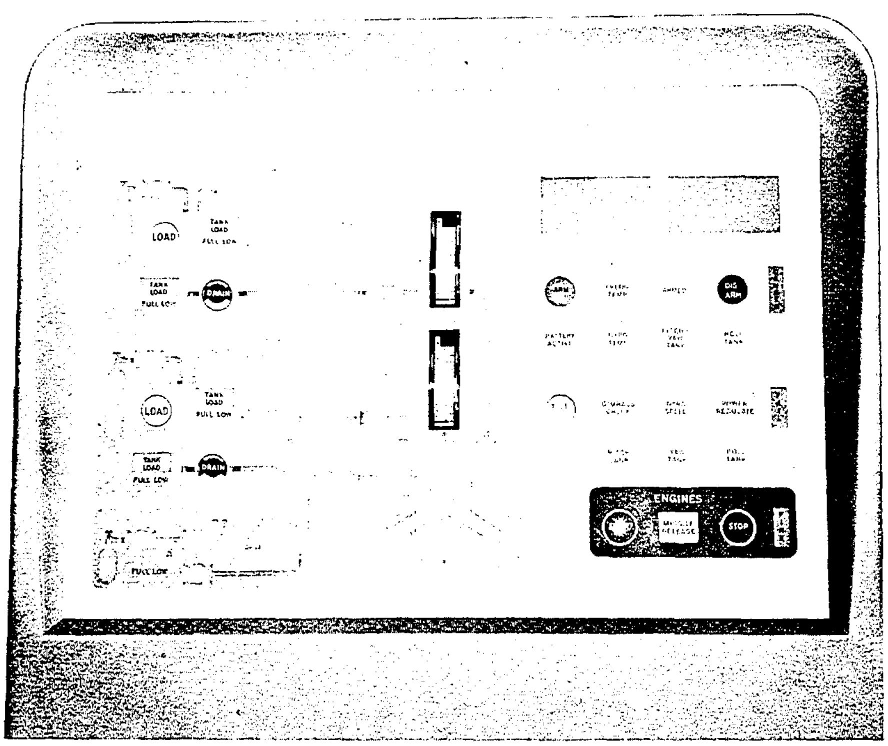

Fig. 5. Double-panel prototype.

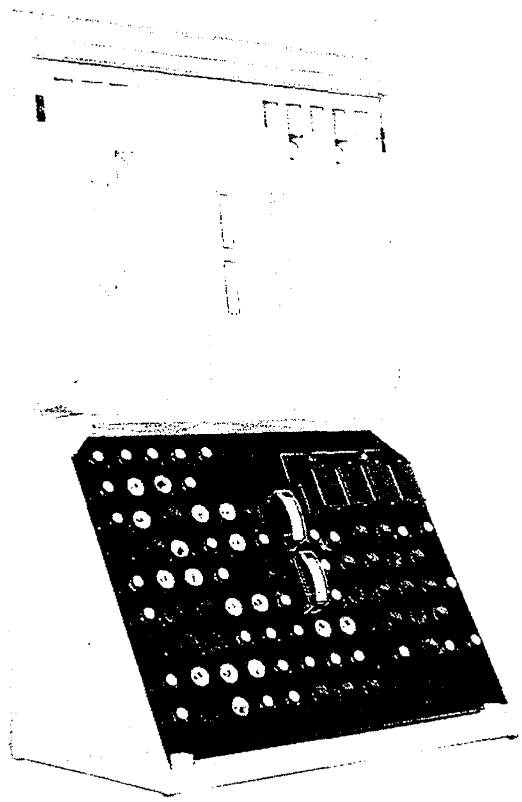

Fig. 6. Double-panel prototype (dress panel raised).

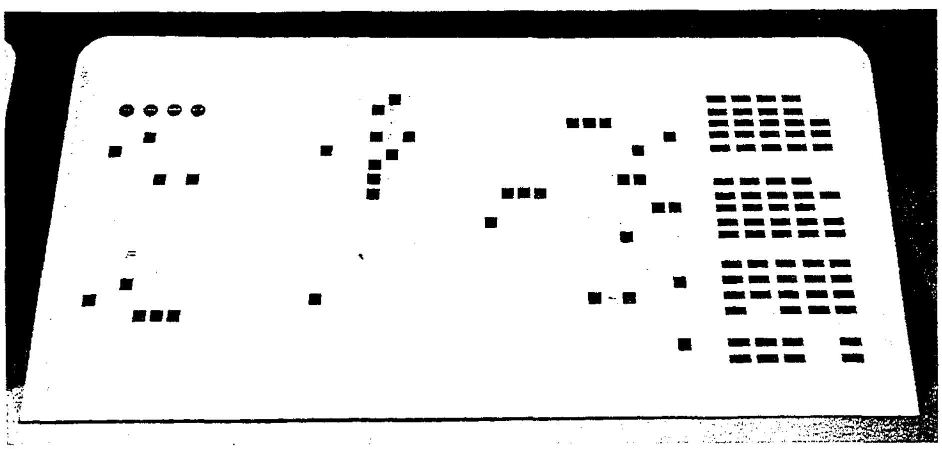

Fig. 7. Atlas analyst console.

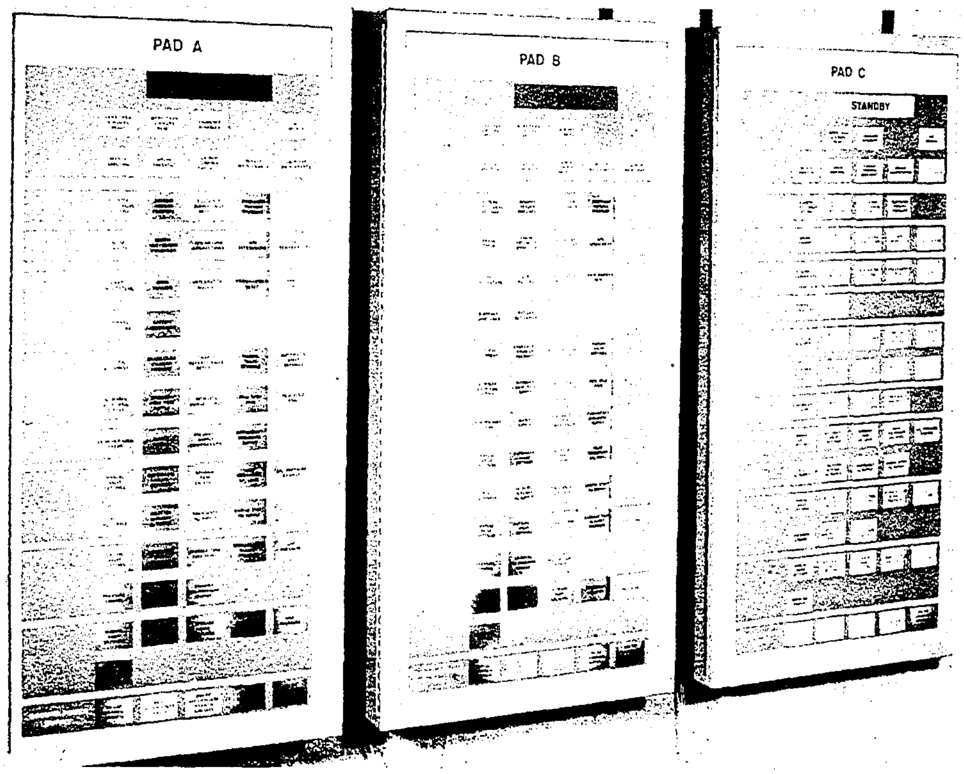

Fig. 8. Atlas status panels.

when discrete indicators and pushbuttons are primarily used. Use of rotary controls requires that clutches be used to disconnect knobs from components (potentiometers, encoders, etc.) when the dress panel is raised.

Double-panel construction provides the best appearance of the panel techniques mentioned. All mounting hardware is covered by the dress panel so only control/display components are shown; simplifying the panel appearance. In addition many kinds of control/indicator components may be used with the dress panel ensuring uniformity of appearance. Figs. 9 and 10 which picture a display panel used in the BMEWS system illustrate this.

Some changes can be made relatively easily if provision is made in the initial design of the panel. For example, indicators can be added easily, if egg-crate light baffling is provided when the panel is built. Addition of an indicator then requires removing the paint on the dress panel where the indicator will occur, and adding the indicator component to the subpanel. Because the subpanel is completely covered by the dress panel, it may be machined to accept additional components or even have the components installed. More major changes, however, are difficult to make.

The high cost of changing control/display panels has been caused by having to replace an entire panel when changes are required. Therefore, it is necessary

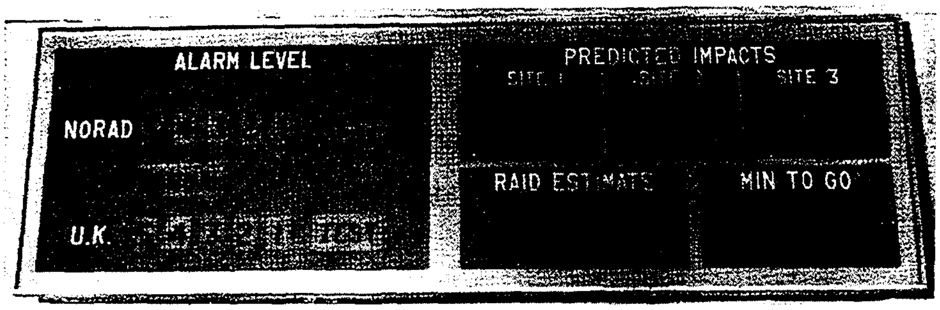

Fig. 9. BMEWS threat summary panel.

to break up panels into easily replaceable units to significantly reduce the cost of changing them.

Early in the development of a flexible panel technique, it became apparent that three key factors, which are related to unit size, would have to be taken into account. These are initial cost, cost to change, and packing factor. It is apparent that the two cost factors are important. The importance of the packing factor, or control/indicator units per unit area, is perhaps not so apparent. At times, however, it is of overriding importance. The 6- by 8-ft panel shown in Figs. 2, 3 and 4 was very difficult to construct simply because of its size. It was also at the upper limit in height that would allow it to be mounted and viewed in the room, which has a 9-ft ceiling height. The system control and switching (Fig. 1) console is another example of an equipment in which packing factor was a very important consideration. The 64-in. width of the panel of this console approaches maximum width for convenient one-man operation. Less-dense packing would have degraded the utility of this console.

Unfortunately, these three factors are interrelated so that it is not possible to choose a unit size that will minimize both initial cost and cost to change, and maximize packing factor. For example, the most flexible panel (lowest cost to

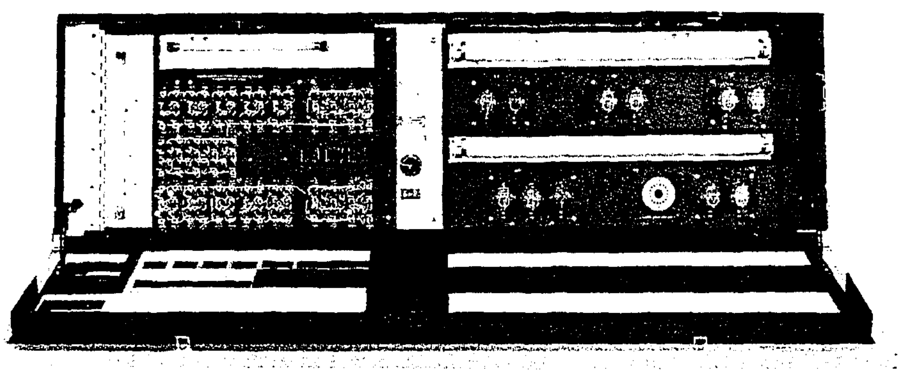

Fig. 10. BMEWS threat summary panel (dress panel hinged-down).

change) would be broken up so that each unit housed a single component. In order to be able to shift such units around at will, however, they must all be the same size, or at least have modular dimensions. This situation is difficult to achieve with the great variety of control/display components which may be used. To maintain one or even a reasonably small number of unit sizes would be wasteful of space since the unit or units would have to be sized to handle the largest control/display component to be contained. This would decrease packing factor. Initial cost would be increased because of the necessity for providing fastening hardware, connectors, etc., for each unit. On the other hand, using the largest possible unit size (not breaking up the panel at all) results in a low initial cost and high packing factor, but a high cost to change.

To optimize unit size individually for all cases would require a detailed study of each case. It would be necessary to attempt to predict how many changes would be made and the general nature of these changes. It would also be necessary to set some value on the importance of the packing factor. It was felt that this sort of study of every case individually would be too time consuming and expensive to be practical. This suggested that we might profitably eliminate both extremes (single-component size units and entire-panel size units) and see if there were any points in the area between the extremes which offered an especially good combination of initial cost, cost to change, and packing factor.

Consideration of the problems of handling joints between units led us to our eventual solution. Joints are a problem for two reasons. First, they must look good. Joint lines should be straight and of constant width. In addition, adjacent units must match in color. Second, joints must be at least drip-proof and perhaps resistant to salt spray or immersion.

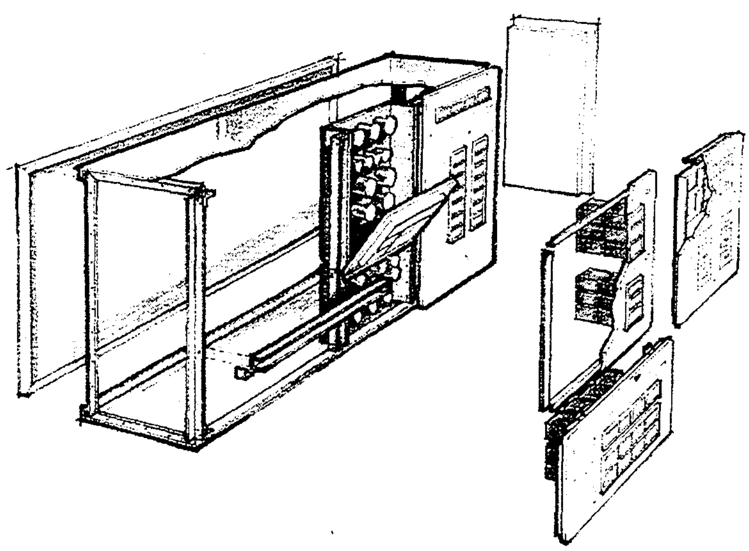

Fig. 11. Modular-panel concept, typical control and display assembly.

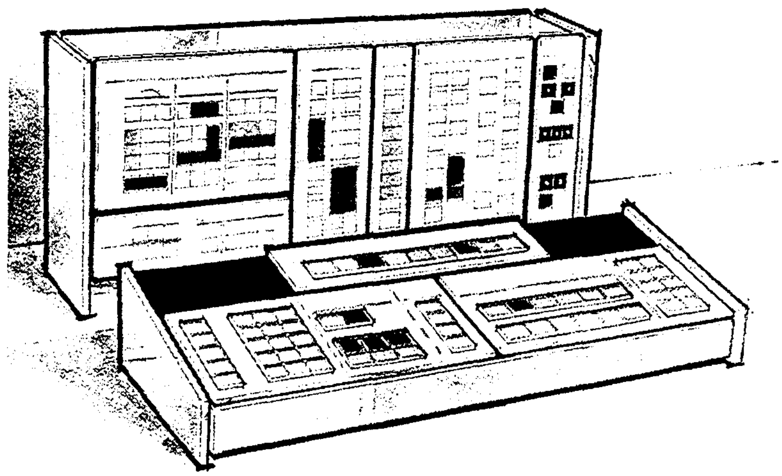

Fig. 12. Manual-input panel and equipment status display, CC and DF.

Breaking panels up on a functional-area basis, as shown by Fig. 11, solved the joint problem satisfactorily. This break-up offers two other important advantages. It saves space, thus increasing packing factor. It does this by using the space which would be left between functional areas to provide visual separation to provide for mounting hardware for the units. In addition since most changes seem to be confined to one or, at most, several functional areas, it reduces the cost of changing by allowing the unchanged units to be reused with no modification. Figs. 11 and 12 show in concept the technique which will be used in producing a set of BMEWS displays. Detail design of these displays is now underway.

DISCUSSION

Q. (K. A. Allebach, Nortronics, Palos Verdes, Calif.) I wondered if these panels were all control panels? Do you have switches on these panels or just indicators?

A. Most of the panels contained both switches and displays (both controls and displays). A few of them, notably the equipment status panel—a large wall panel—were display panels only.

Q. In our company we have a running battle as to whether we are going to use old-fashioned toggle switches or make it completely pushbutton, so I was wondering what you were using?

A. We make the determination on the basis of the function of the panel. There are advantages to toggle switches; they are easy to operate quickly and they are quite inexpensive. They have a disadvantage in that they are quite easy to inadvertently operate. In situations where inadvertent operation of a control would be disastrous, we stay away from toggle-type switches and go to something a little safer.

Q. (Ed Cormier, General Dynamics/Astronautics, San Diego, Calif.) How do you reconcile this modularized paneling in control consoles with current trends to identify allowable choices to the operator by means of lighted arrows between the functions? I don't really see where your flexibility is, because I have used these double panels and there are two things to change instead of one. The baffling has to change if you change a button from one place to another.

A. I didn't mean to imply that the flexibility I was talking about with regard to the double panel meant that they were easy to change. By flexibility here I mean that we can choose from an unlimited variety of indicator shapes and sizes in order to code symbolically indications on a panel making a complex panel somewhat easier for an operator to comprehend.

printed circuit boards
[illegible]

Packaging the Lenkurt 76A Microwave Radio

STU ALESHIRE

Lenkurt Electric Co., Inc., San Carlos, California

This paper describes the packaging of an advanced design broad-band radio transmission equipment in the common carrier band, 5925 to 6425 Mc. The entire packaging concept is covered in general with particular attention paid to provisions for straightforward installation, ease of testing, servicing, and maintenance. Heat sinking of the klystron is given particular attention. Several unique production techniques, developed by Lenkurt, and their effect on design are examined. The use of industrial designers and their contribution to the package is brought out. The final package as a whole is critically examined and the author's opinion as to future development is given.

INTRODUCTION

THE LENKURT TYPE 76A Microwave Radio is a broad-band transmission equipment in the common carrier frequency band, 5925 to 6425 Mc. The particular option to be dealt with consists of two transmitters, two receivers, an alarm shelf, a combiner shelf, a transmitter auxiliary shelf, a receiver auxiliary shelf, and power supplies; Fig. 1 shows this arrangement.

Lenkurt equipment is supplied to operating sister subsidiaries of General Telephone and Electronics, any of the several hundred independent telephone companies, the Bell System operating companies, railroads, pipeline companies, and other industrial users with requirements for long-haul multichannel voice or data transmission. The various branches of the armed services, as well as other government agencies, are also users of Lenkurt equipment. The environment in which the equipment is used, the capabilities of maintenance personnel, the existing state of the art, as well as industry standards all contribute to the general mechanical specifications.

SPECIFICATIONS

1. Equipment to be mounted in a standard 19-in. relay rack. The 76A proper to mount in an 8-ft.-high self-supporting rack. Envelope limited to 5 in. in front of rack and 10 in. total depth overall.

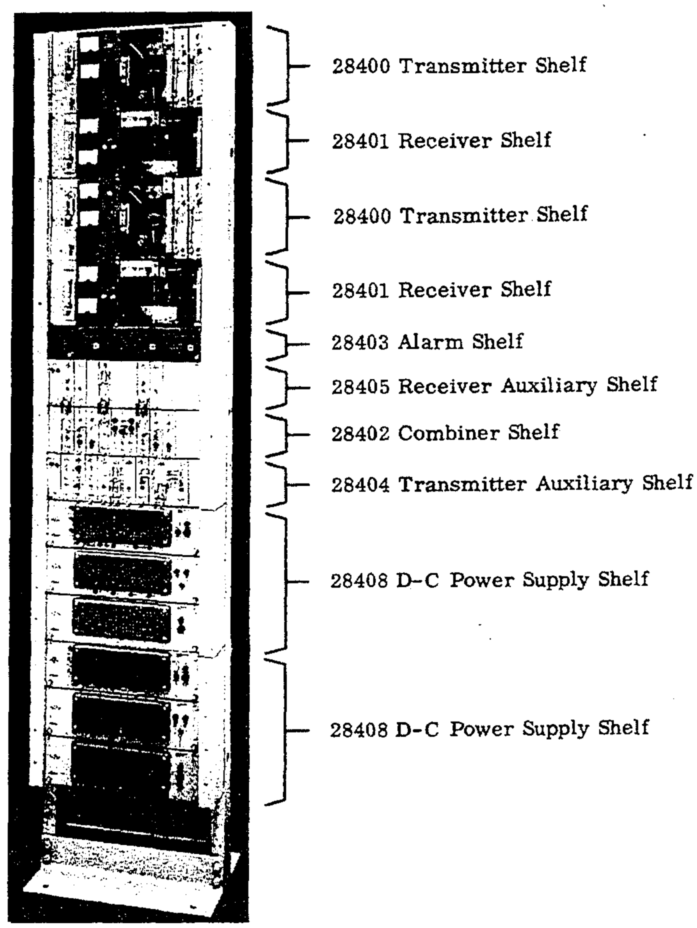

Fig. 1. Lenkurt type 76A microwave rack layout.

2. For ease of installation, and to allow back-to-back installation, equipment to have front access.
3. Interchangeable plug-in units to be used where possible. The plug-in concept to apply up to the transmitter and receiver assembly level.
4. Test points and adjustments to be accessible from the front with the removal of a minimum of equipment.
5. Equipment to be interlocked for removal of all dangerous voltages during servicing.
6. Compatibility with existing equipment.

In addition to these general specifications, further Lenkurt design criteria were set. These design parameters were based on either current engineering philosophy, manufacturing practices, and/or state of the art. Lenkurt-originated specifications were:

1. Solid state devices throughout except for klystrons.
2. No ovens or blowers to be used.
3. Lenkurt 46A carrier universal mechanics with stitched wiring cards to be used where applicable.
4. Printed circuit boards to be used only to supplement stitched wiring cards.
5. Design for 20-year life.
6. Environmental Conditions:

Temperature	32° to 122°F
Maximum Altitude	15,000 ft
Maximum Humidity	95%

7. The use of only well-tried and proved components.
8. Equipment to be shippable rack-mounted and designed to stand shipping environment.

PRELIMINARY STUDY

Preliminary study of the design problem coupled with data from previous microwave systems established that klystron cooling would be the principal criterion for any proposed design. This plus the lack of data on heat dissipation available from klystron manufacturers led to the decision to do preliminary work in this area before starting actual packaging design.

An extensive heat transfer study showed that the particular klystron, Type 222, chosen for use in the 76A transmitter dissipates some 65 w in heat when operating at full power. This heat rejection breakdown is approximately 45 w through the heat exchange flange to the heat sink chosen, 7 w to the waveguide and 10 w to the surrounding air. The klystron for receiver use dissipates only 12 w in heat and so emphasis was obviously placed on the transmitter tube.

Incidentally, a valuable by-product of this testing was the method developed for attaching thermocouple leads to the tube body without soldering. This method involves the following:

1. The two thermocouple wires are spot-welded together, and then a relatively large solder ball is formed on the two spot-welded leads.
2. A small hole is drilled into the tube, at the point where the measurement is to be taken, and slightly countersunk. The solder ball lead is then peened into the hole with a small peening tool until the wire junction is approximately flush with the surface.

Based on data from the study just discussed, the decision was made to use a heavily finned cast-aluminum heat sink for klystron cooling. Since costly waveguide alignment problems normally encountered are minimized by taking advantage of the heat sink's rigidity and mounting the waveguide directly on the plate, such a procedure is obviously indicated.

EQUIPMENT DESIGN

Transmitter

The transmitter heat sink with klystron and associated waveguide mounted is shown in Fig. 2. The heat sink proper is of sand-cast Alcoa 356 aluminum. The boss for klystron mounting is an integral part of the casting. The klystron mounting surface is ground and lapped for maximum heat transfer. Silicone grease is used on assembly and every effort is made to assure heavy clamping forces. Ideally, these clamping forces would be furnished by screws through the klystron flange. Unfortunately, in the transmitter the requirement for accessibility ruled this out. As an alternative, the clamp shown in Fig. 3 (versions *A* and *B*) was developed. Version *A* is used for clamping the klystron to its heat sink boss. Version *B* is used for clamping the klystron to the waveguide flange. These clamps, made up of investment-cast parts and commercial components, have proved to be quite satisfactory.

Because of the transmitter-to-receiver waveguide manifolding, the basic mechanical arrangement of both (receiver and transmitter) was fairly well defined by the transmitter heat sink choice. The arrangement, shown schematically in Fig. 4, involves the heat sink or mounting plate on the back of the rack, with the klystron to the right side. The waveguide plumbing is flex-mounted on the heat sink or back plate. The waveguide manifolding to the antenna lead is along the right side, parallel with and within the rack. The waveguide flex-mounting used is a combination cork and neoprene compound, manufactured by TA Manufacturing Company. A typical mount is shown in Fig. 5.

The location of the waveguide plumbing between the rack frames, which seems almost mandatory, does have its attendant problems. One of these is providing accessibility for klystron replacement. Another of equal if not greater difficulty is

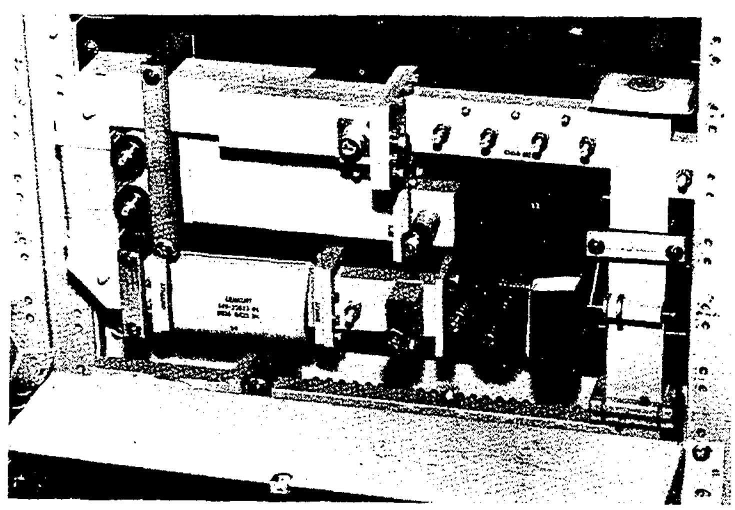

Fig. 2. Klystron heat sink.

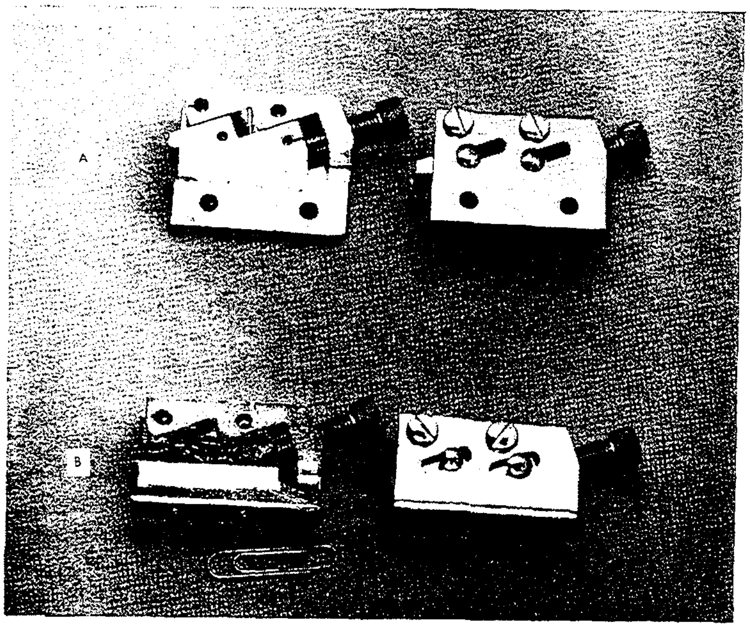

Fig. 3. Klystron clamp.

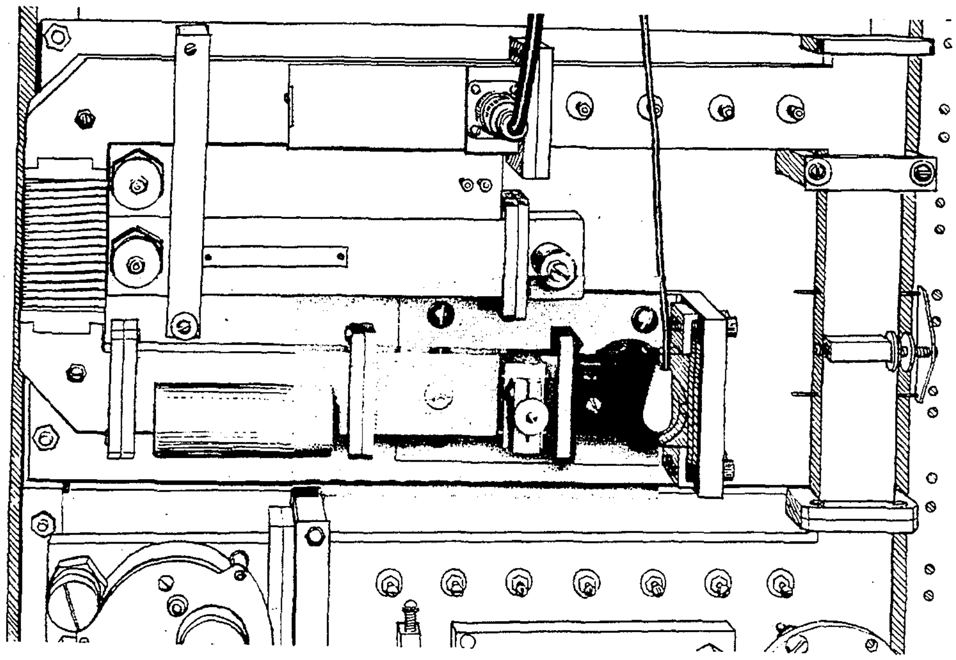

Fig. 4. Waveguide manifold.

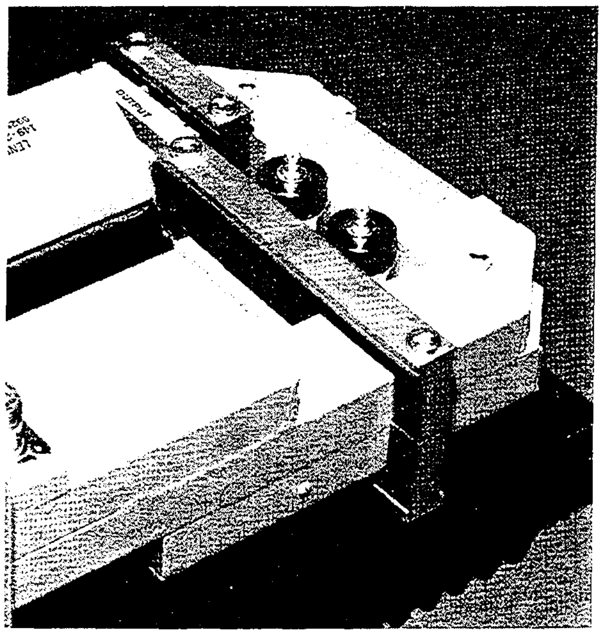

Fig. 5. Waveguide mount.

accessibility to the various tuning screws on both transmitter and receiver. The required accessibility points are shown diagrammatically for the transmitter in Fig. 6 and for the receiver in Fig. 7. The key to the type of adjustment is the same in both figures. Those components requiring accessibility for replacement are marked "replace" on the diagrams. A further complication arises from the fact that some of these adjustments must be made in service, i.e., with the power on. A still further difficulty is caused by certain Canadian requirements that high voltages be screened with covers to have no access holes exceeding $\frac{1}{4}$ in. in diameter.

The waveguide unit-to-unit interface presented another accessibility problem. The requirement that any top assembly, i.e., any transmitter or receiver, be removable without removing parts of adjoining assemblies precluded the use of flange bolts. For this reason, clamping and alignment here was accomplished through the use of a clamp developed by Marman, and a keyed spacer.

Due to the many facets of the accessibility problem the decision was made to have all units in front of the waveguide assemblies, or perhaps more properly all units in front of the racks, either plug-in or in a similar manner readily removable. This led to some rather sizable plug-in units. The transmitter meter box shown in Fig. 8 is an example. This package contains the meters and their associated networks as well as switches for metered function selection. The meter box also encloses the klystron power distribution terminal. The female section of the power interlock is mounted on the klystron side of the meter box. The klystron protection diode is also found in this area.

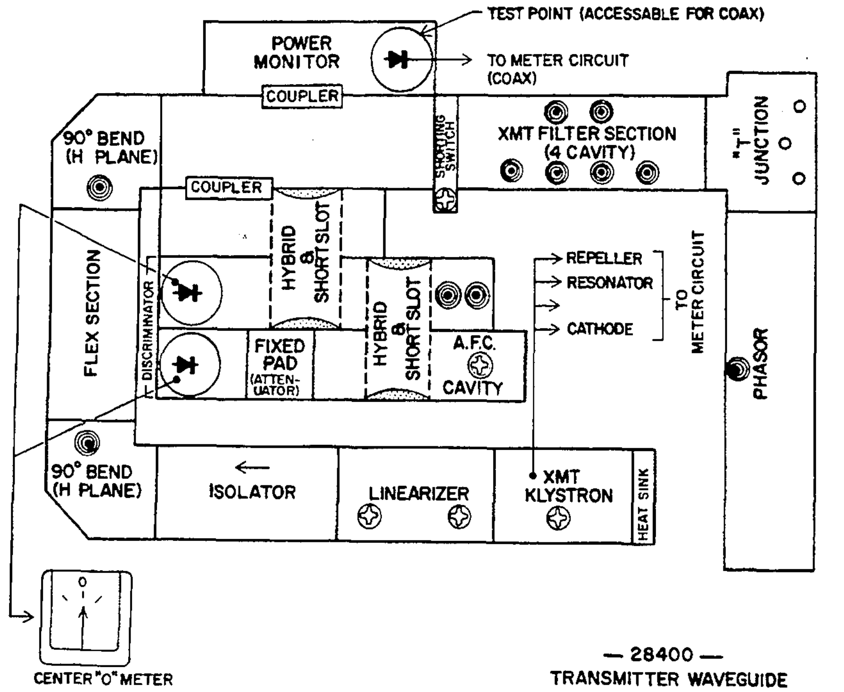

Fig. 6. Transmitter manifold access points.

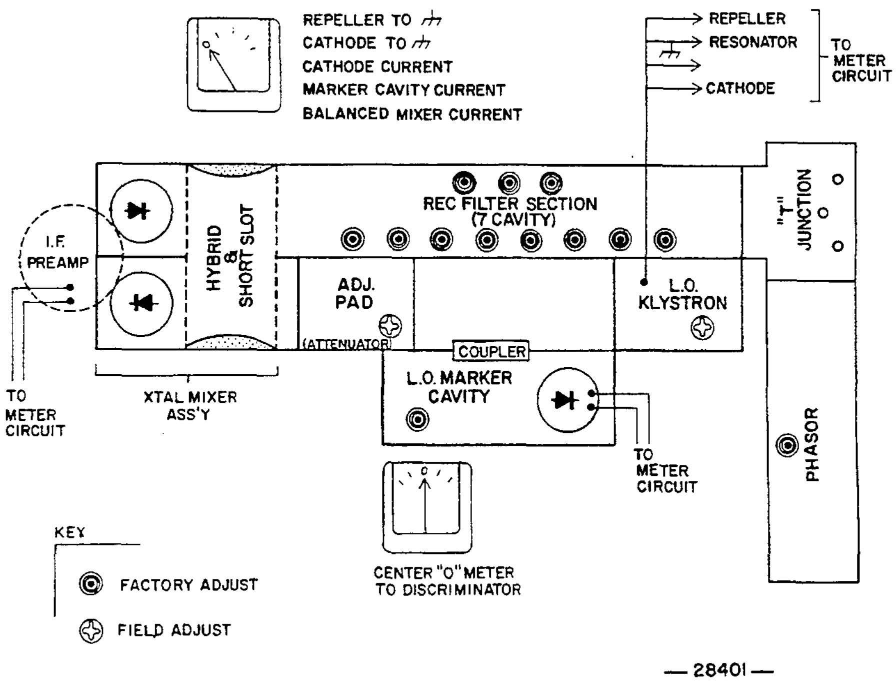

Fig. 7. Receiver manifold access points.

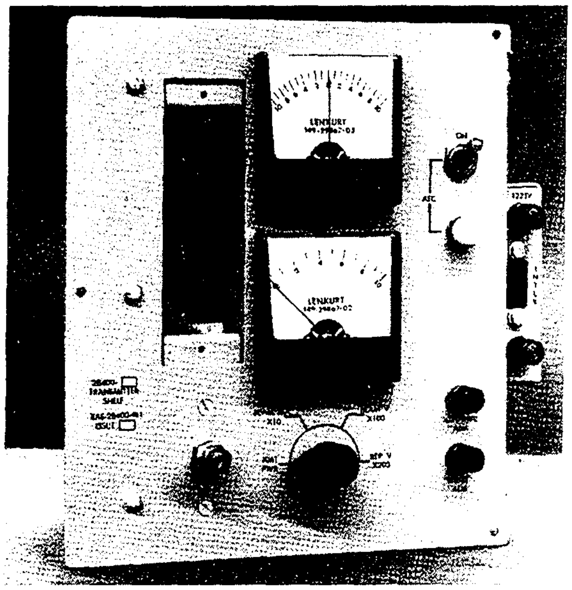

Fig. 8. Transmitter meter box.

Alarm and pilot lamps are located on the meter box front panel, as are "Power On" indicator lamps. A skirt on the left of the meter box covers the transmitter terminal block and also carries the transmitter power monitor unit, a plug-in card. The rack and panel type of connector is carried on the back of the meter box. The entire meter box assembly is guided and supported by slides and nylon buttons of the type developed for the power supply drawers.

In both transmitter and receiver the area immediately to the right of the meter box is covered by a hinged door. The door when open allows access for klystron tuning and for checking the protection diode, as well as access to the various tuning points on the waveguide. The male portion of the power interlock is mounted on this door in a somewhat novel fashion (see Fig. 9). In normal operation the U-shaped metal prong acts as a jumper to provide continuity. As the door is opened the circuit is broken and the power removed. On those occasions when it is desired to cheat the interlock, the plastic handle is unscrewed allowing the door to swing open without the jumper.

Still further to the right are two more plug-in units: the modulating amplifier unit and the transmit pilot detector unit. These units are both printed circuit boards similar to those previously discussed.

Receiver

From an appearance standpoint the receiver shelf on the 76A is quite similar to the transmitter. The meters and their panel location, as well as their controls and lamps, are approximately the same. Again the meter box is a sizable plug-in

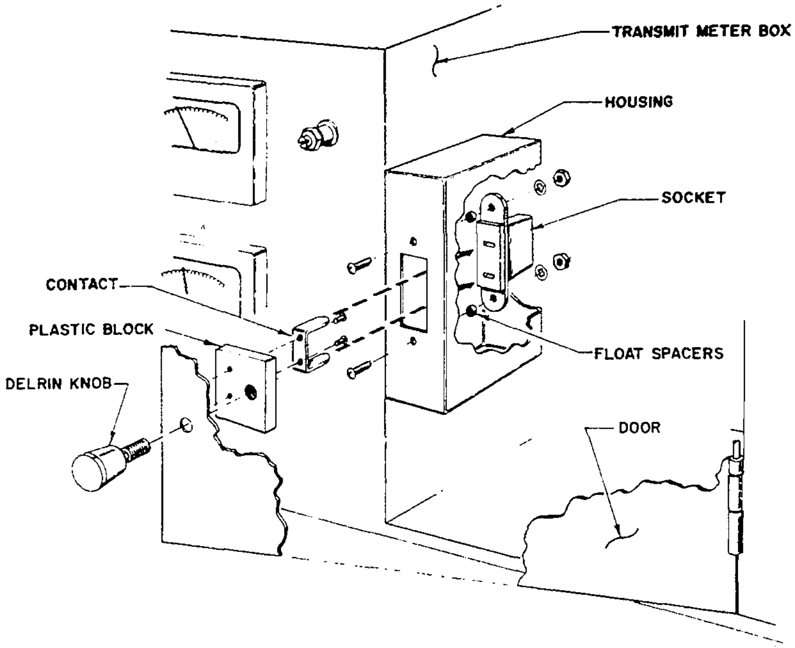

Fig. 9. Power interlock.

unit with a skirt to the left carrying a plug-in card. This card contains AFC circuitry. Also similar to the transmitter is the access door to the right of the meter box. These doors, incidentally, have gone through quite a process of evolution.

Once the basic design philosophy to be followed on the 76A was settled, a firm of industrial designers (Melvin Best & Associates) was called in for consultation. As a result, extremely helpful recommendations concerning equipment appearance and organization were made. Figure 10 is a sketch of the equipment as proposed. Features of particular interest are the grouping of meters and controls and the doors, right and left, covering operating components. While some compromises were necessary the first rack of 76A equipment did closely approximate the suggested design. Figure 11 shows the prototype of this design.

This first rack was given an advance showing to field representatives and subsequently was displayed at the USITA Convention. On both occasions comments on the equipment's appearance were favorable. In the final analysis, however, there were questions as to the practicability of the design. The doors to the right and left of the meter boxes did present some difficulties: alignment was one. One large door for each side would, of course, solve this problem but would reduce the flexibility of rack arrangement. The next consideration was the use of individual plastic covers rather than metal doors. A sample rack with this design is shown in Fig. 12. Very obviously, this left something to be desired from an appearance point of view. The compromise using individual partial doors of metal on the right side only was finally worked out (see Fig. 13).

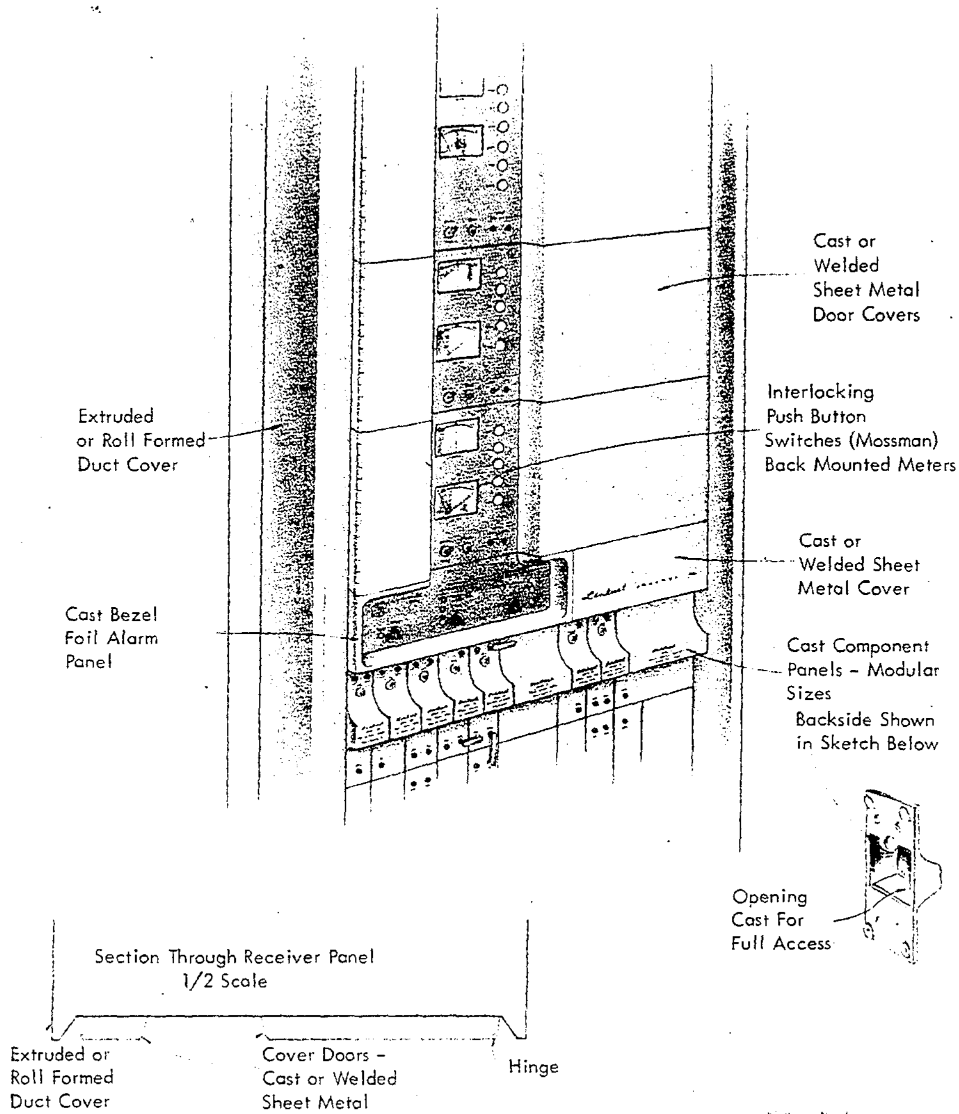

Fig. 10. Industrial designers proposed layout.

Alarm Shelf

Immediately below the bottom transmitter or receiver is the alarm shelf. The drawer portion consists of a somewhat conventional chassis carrying the major and minor alarm relays and their networks. The front panel carries alarm lamps and alarm cutoff switches. These switches contain their own indicator lamps and are push-to-operate type. One of the salient features of the alarm drawer is the

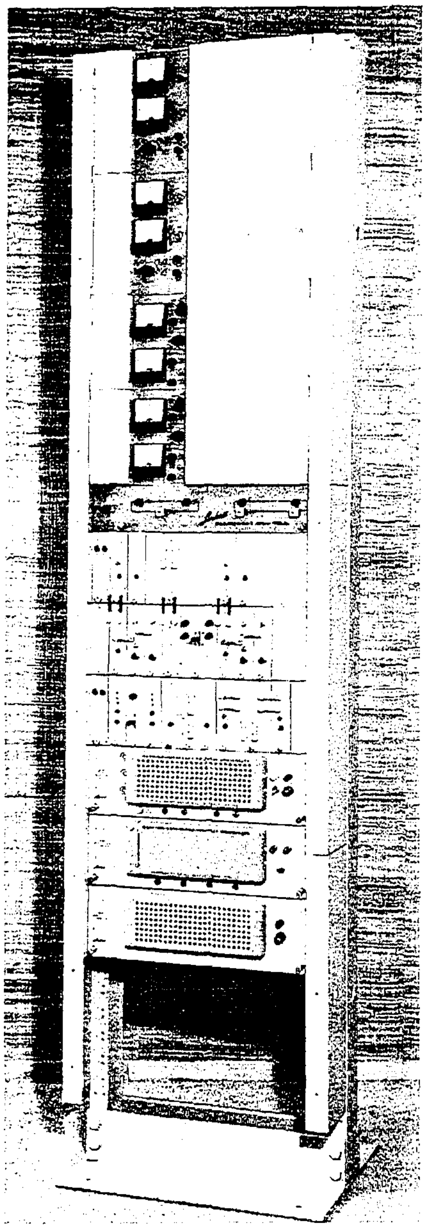

Fig. 11. First prototype 76A.

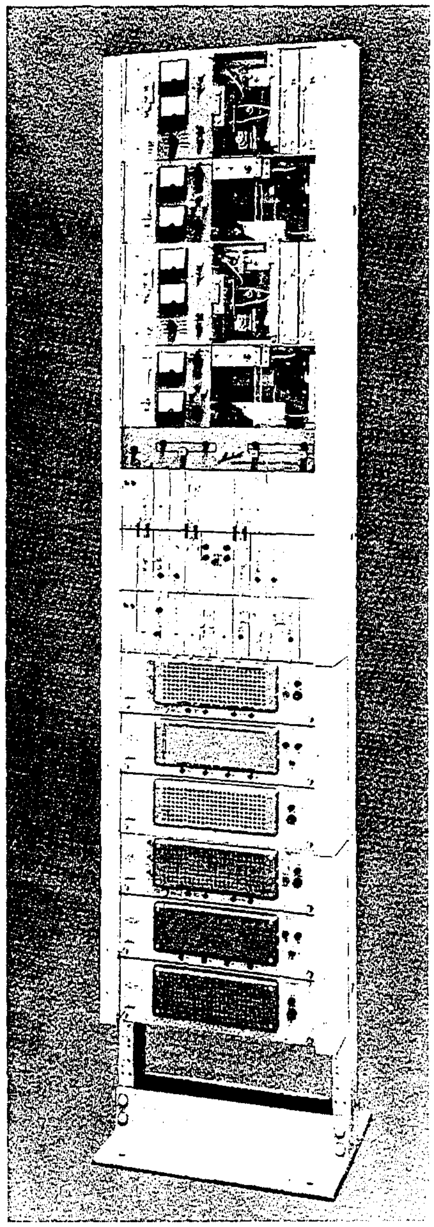

Fig. 12. Second prototype 76A.

use of precoiled cable, furnished by Spectra-Strip Wire and Cable Corporation, allowing the drawer to be pulled out for checking without the usual cable support problems (see Fig. 14).

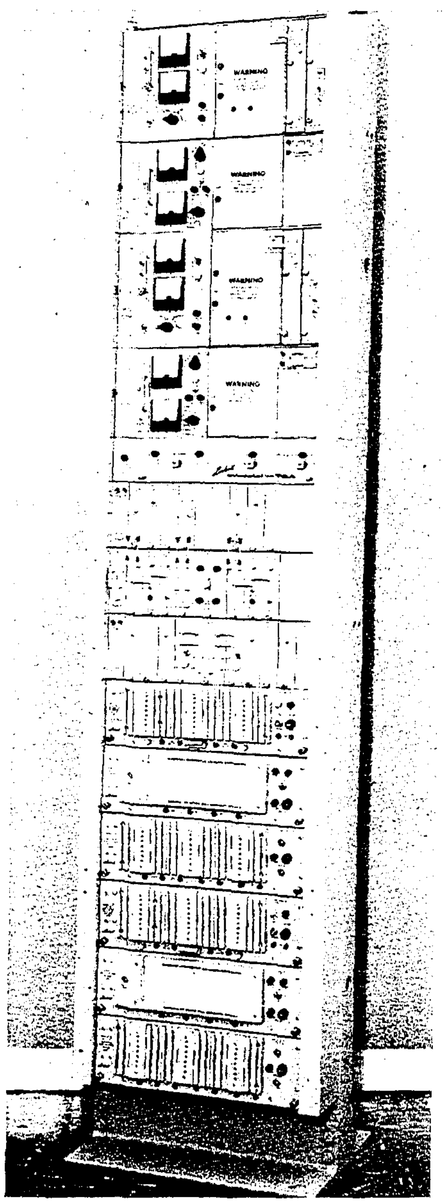

Fig. 13. Final version 76A.

Auxiliary Shelves

Normally located below the alarm shelf are three auxiliary shelves: the transmitter auxiliary shelf, the receiver auxiliary shelf, and the combiner shelf. These shelves contain various combinations of equipment on plug-in stitched wiring

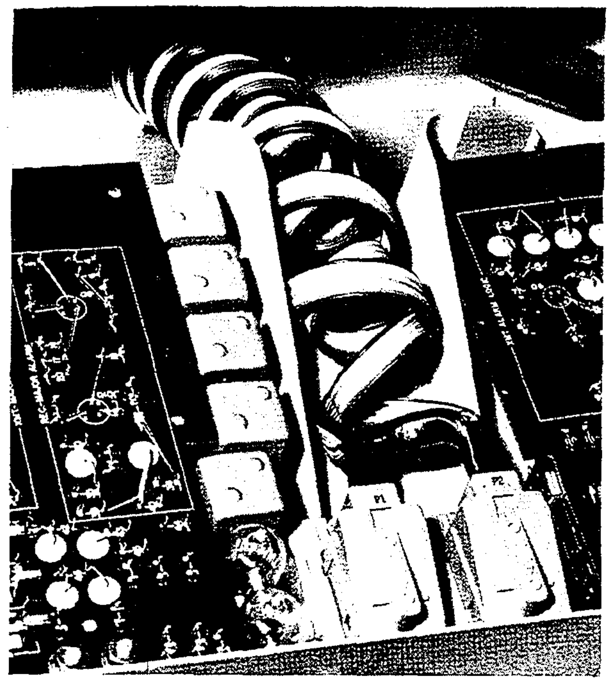

Fig. 14. Spectra-strip coiled cable in alarm drawer.

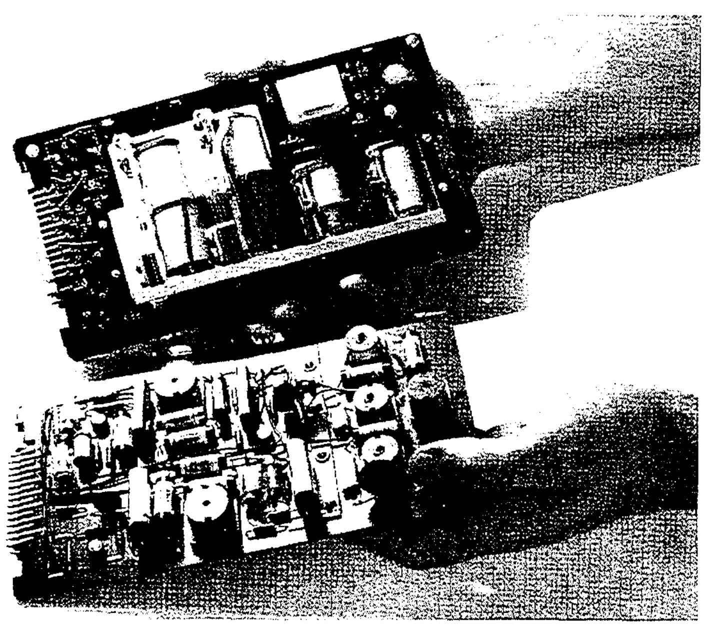

Fig. 15. Typical stitched-wiring circuit boards. Large components may be accommodated by spacing two or more boards apart on a modular basis.

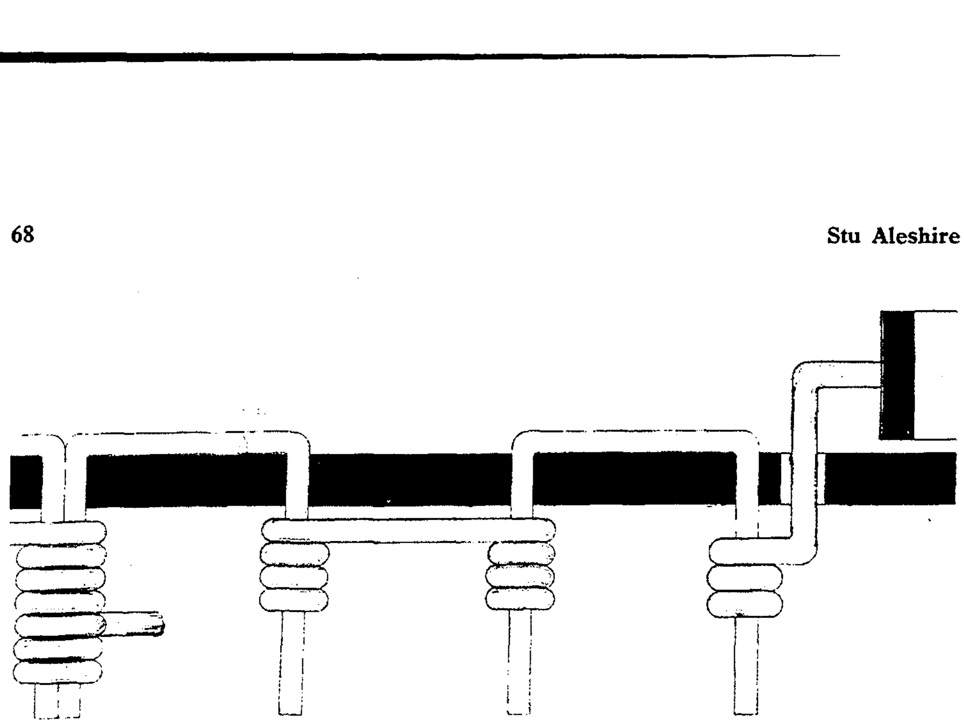

Fig. 16. The stitched-wiring principle illustrated. The staples are driven through the board without prepunching. Component leads pass through adjacent holes and wrap around staple posts. Staples are interconnected with barewire straps. Entire board is dip-soldered.

cards mounted in what Lenkurt designates as universal mechanics. Since stitched wiring is a process developed by and peculiar to Lenkurt, some detailed description seems worthwhile.

In the *stitched-wiring process* an insulating board (black XP phenolic) is used as in printed or etched wiring. Boards are sheared or ~~blanked to size~~, punched or drilled, and designations are silk-screened. Here the similarity to printed wiring ends. The copper laminate is dispensed with and tin-coated bronze staples with either hand- or machine-wrapped wiring is substituted. Each staple becomes a terminal. As in printed wiring, components are normally located on one side of the board, with wiring on the other side. Component leads and wire connections are securely wrapped around staple legs for mechanical and electrical integrity. Hand- or dip-soldering gives an additional margin of safety. Male connector pins are inserted as required. Figures 15, 16, and 17 show details of stitched wiring. Lenkurt has found stitched wiring to be economical, reliable, and serviceable.

Power Supply Shelves

Power supply shelves follow accepted industry design standards. The drawer slides (Fig. 18) developed for use here are perhaps worthy of note. Slides consist of plated steel angles with nylon buttons for bearing. The slides are rugged and economical, certainly a fair trade-off for the costlier commercial items available.

CONCLUSION

The packaging effort on the 76A has resulted in an attractive, serviceable piece of equipment meeting the original design parameters. While certainly not the

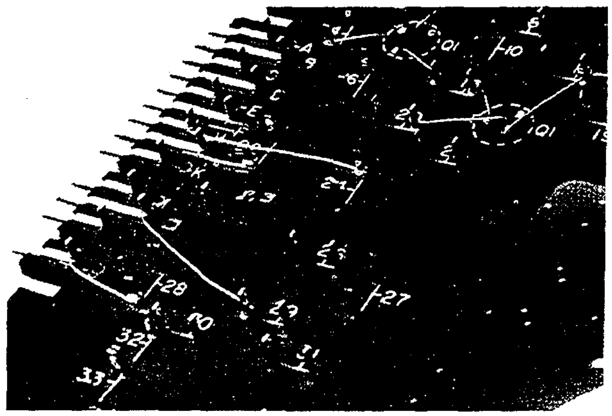

Fig. 17. Detailed close-up of preformed male connector pins after insertion in board, wire-wrapping, and soldering. The gold-plated pins maintain good electrical characteristics under adverse conditions, and avoid suffering the effect of wear sometimes encountered in printed connectors.

epitome of design, it does show improvement over its predecessors and will be a sound base for further improvements in the future.

PROGNOSTICATION

Tomorrow's 76B or C or D will probably find more and more emphasis given to industrial design and human factors. The klystrons remaining will be replaced by solid state devices allowing reductions in power consumption and reduction in power supply size. Equipment overall sizes will shrink by probably 50% as new techniques are adopted. The use of plug-in units for serviceability will necessarily follow. Package size reduction and cooling problems are inseparable. More exotic cooling systems seem inevitable.

In summation, the role of the packaging engineer promises to grow exponentially. It should be fun.

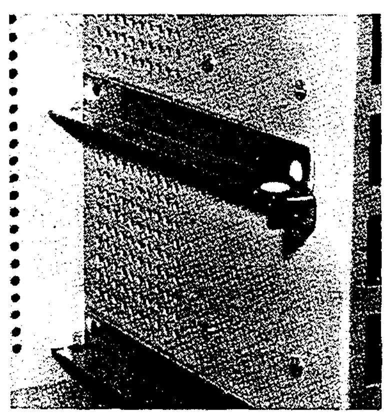

Fig. 18. Slides.

ACKNOWLEDGMENT

The author acknowledges with thanks the encouragement given by Maurice Kebby, Microwave Project Manager, in the preparation of this paper. Also, thanks to members of the Microwave staff for help in preparation and editing. Particular thanks to John Coffin, Production Engineering Manager, for permission to draw on his paper: *AIEE Transactions* **61**, 1046, "A Stitched Wiring Process for Miniaturized Communication's Electronics," Coffin and Johnson.

DISCUSSION

Q. (D. A. Beck, Bendix Research, Detroit, Mich.) You mentioned in the paper that the klystron mounting surface was ground and lapped.

A. No, if I did I was wrong. The *mounting surface* for the klystron or the boss the klystron mounts on is ground and lapped.

Q. As far as my question goes it would mean the same thing. Why did you go to the extra trouble of lapping and then using silicon grease?

A. Our test told us it was necessary.

Q. You wouldn't get enough contact with the ground surface. I would think you would get better contact.

A. We had better results when we ground and lapped and used silicon grease. We ran quite a few tests. I won't say they were exhaustive, but they were enough to satisfy us that it was necessary. Believe me, we don't like to spend money.

Q. I gathered that. Now, when you are stitching the boards, does the length of the stitch vary?

A. I had hoped to avoid this. I have three more slides on stitched wiring. Let me show you these slides and perhaps they will answer the question. This is a schematic through a section of our stitched wiring. Lenkurt, incidentally, used stitched wiring in conjunction with . . . or I should say used printed circuits in conjunction with stitched wiring. We consider this part of our standard mechanics. These staples are inserted in the boards and they use this as a terminal in the board. The staples are standard. The spacing is standard. There is a hole drilled for the components beside each staple and the component lead is brought through and wrapped around the leg of the staple. If we want a jumper we can jumper as we have shown or we can use insulated jumpers if we need to get across components.

Q. Then you put a stitch off the end of each component. Is that it?

A. That is right. There is a staple for each component. Now we can run more than one component to a staple and the staples can be at an angle. We try to avoid angles if we possibly can.

Q. Let us say they are means of connection to the component rather than connection between components.

A. They are an economical way of providing a terminal. This is a picture of the component side of a typical stitched wiring card. You can see these flat portions here. The hump on the staple is right here and here. We make our own connectors, I mean we make the male portion. That is pretty much the same setup. On these heavier components, we use solid leads as much as possible. We try to keep any jumpering off this side of the board. You see there is some jumpering there but we try to avoid it as much as possible. The machines are at the Lenkurt plant to automate this process. This is the wiring side of the staple board. You see a lot of jumpering here.

Q. (John Rykaczewski, Martin-Orlando, Fla.) Was any material with a higher thermal conductivity than aluminum used for the heat sink?

A. No. Aluminum was the beginning and the end of our sinking on these things.

Q. According to your paper, you say an extensive heat transfer study was made on this.

A. I worked in military products before I joined Lenkurt. In military when I talked of an extensive study I meant ten years and two million dollars. At Lenkurt I mean two weeks and a small budget.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) Getting back to that stitch circuitry, wouldn't it be more economical to use printed circuit boards instead of the hand labor necessary to make the interconnections between the staples?

A. I personally feel there are many advantages to printed circuit boards, and I think perhaps that Lenkurt is beginning to see this. I know that just before I left we were told that the 76C would be all printed circuit boards.

Q. Any problems with the interconnection of keeping fidelity of a signal because of the frequencies at which you are operating?

A. Right, there are problems. We would like to avoid those antennas, if we can—and we will.

Q. (Bob Gerlach, AC Spark Plug Div., GMC, Milwaukee, Wis.) On the stitched wiring again: Number one—are those stitches a standard product that can be purchased? Number two—are they cemented to the boards?

A. They are machine-formed from strip wire at insertion. They are not cemented to the boards. They are pressed in, we don't predrill the board for staples. We press the staple in and the problem is not to keep them in but to get them out if you have to.

Q. (David Walker, Sperry Gyroscope, L. I., N. Y.) You mention a 20-year design life. What is your assurance of the 20-year life?

A. Well, we run as many accelerated life tests as we can and collect as much data as possible, and we have had equipment out in the field for a number of years. Lenkurt has a pretty good name in the carrier and radio fields. Our customers seem to feel that if we tell them 20 years—they will risk it.

Q. (Elmar Kolehmainen, Melabs, Palo Alto, Calif.) I don't have a question, Stu, I just wanted to back you up a little on this 20-year life. This is expected pretty much of telephone equipment but they also figure that you maintain this equipment. This is where the balance comes in; the maintenance of this type of equipment. They expect 20 years, but they don't always get it.

mylar angle
plastic core
glass epoxy ...
molded plastic ...
encapsulation

Packaging for Maintainability of an Airborne Computer: A Case History

LOUIS R. CRITELLI

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This paper discusses a new high-speed, completely transistorized, airborne digital data processor, designed and manufactured at the General Electric Light Electronics Department for the AEW control system of the Grumman W2F-1 Hawkeye aircraft.

INTRODUCTION

A NEW HIGH-SPEED digital computer has been designed and manufactured at General Electric's Light Military Electronics Department for the Airborne Early Warning (AEW) Control System of the Grumman W2F-1 Hawkeye aircraft. This completely transistorized airborne data processor receives and processes information from aircraft radars, and then transfers a digital report to display equipment.

The computer uses a magnetic drum memory with 38 channels capable of storing approximately 100,000 bits of information. Primary clock frequencies are 4.6 Mc, 1.14 Mc, and 574 kc. The logic portion alone contains 789 modules, 733 of which involve 10 different types. This section accounts for 5190 transistors and 14,557 diodes. Transistors are of 17 types, 14 of which are MIL types: 10 of 14 are listed in MIL STD 701B and 7 of these 10 are preferred types.

With such equipment complexity, it was imperative that the designers develop a packaging concept which would make the location and correction of malfunctions easy. The mere fact that the computer was slated for a military airborne environment, with its stringent requirements for equipment availability, made a design for maintainability a guiding principle in the establishment of packaging criteria.

The detector itself, a rigidly mounted equipment, is packaged in a volume of 10.5 ft^3 and weighs 410 lb. For ease of maintenance, a modular design has been used throughout the computer from the ten major aircraft replaceable assemblies (ARA's) right down to the basic 2-oz computer circuit subassembly.

MAINTENANCE FEATURES

One of the unique features of the equipment is the absence of even a single maintenance adjustment. For maintenance aid, three test targets, which check approximately 80% of all of the computer circuits, are self-generated and processed periodically. Fault isolation lights on the maintenance panel provide alarm indication when major functional areas are not operating properly.

Primary test points, which are accessible from the front of the unit when the front panel is removed, permit fault isolation to within approximately ten modules. The use of secondary test points within the unit permits fault isolation to within four modules. To perform preflight marginal testing of the computer, dc voltages are varied $\pm 10\%$, and the clock frequency is increased 10%.

COMPUTER LOGIC ASSEMBLIES

The major portion of the computer circuitry is contained in five mechanically identical pull-out frame assemblies located in the upper section of the equipment. These frame assemblies, each having a circuit module capacity of 163 units and weighing 39 lb, embody a design in which maintenance requirements as well as performance and reliability were considered primary design goals.

Isolation of malfunctions down to the module level is made easier by the availability of and accessibility to numerous test points. This prevails whether the frame assembly is in its operating position or pulled out and locked in its maintenance position.

The pull-out frame assembly, a sectionalized parallelepiped, features an LMED-developed "building block" type of construction as the basic chassis configuration. The frame-type network, while providing an excellent balance between stiffness and weight, offers virtually no impedance to cooling air and, in addition, facilitates optimum accessibility during assembly and servicing of the end item.

The entire left side of the frame (Fig. 1) is covered by the mother plate with its 163 receptacles, wiring harness, and a clear plastic protector cover, while the right side (Fig. 2) features individual module hold-down covers for each small compartment within the frame. To aid the maintenance man in the proper positioning of a module in the pull-out frame, identification coding on the cover matches identical coding on the module's formed lip. At key positions on the cover complex, special marking identifies the function of the secondary test points. (These are the test points accessible to the maintenance man only when the pull-out frame is in its maintenance position.) Special fixtures located on the front face and the lower rear corner of the assembly make up part of the hardware necessary to support the pull-out frame in its maintenance position.

All wiring on the pull-out frame terminates in Bendix pigmy-type, wall-mounted connectors located on the lower face plate of the assembly. This connector was chosen over a rack and panel type (R & P) for several reasons. The major ones were:

1. Small size advantage over an equivalent MS connector.
2. Reliability comparable to the equivalent MS type.
3. Lack of the mechanical complexity associated with a 220-pin requirement in an R & P.

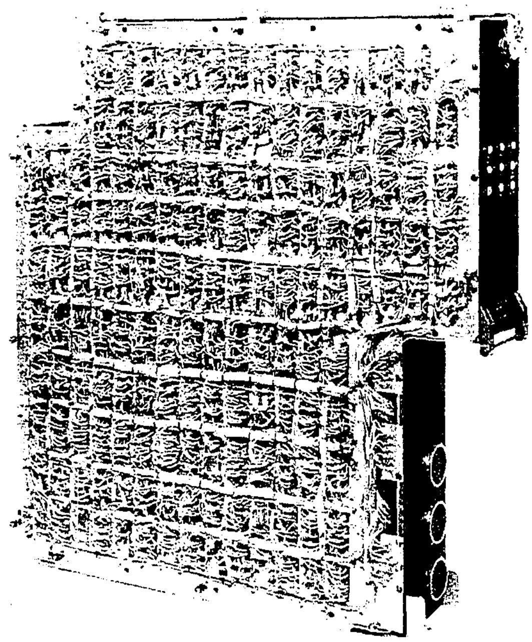

Fig. 1. Left-side view of pull-out frame showing the logic assembly wiring and the plastic protective cover.

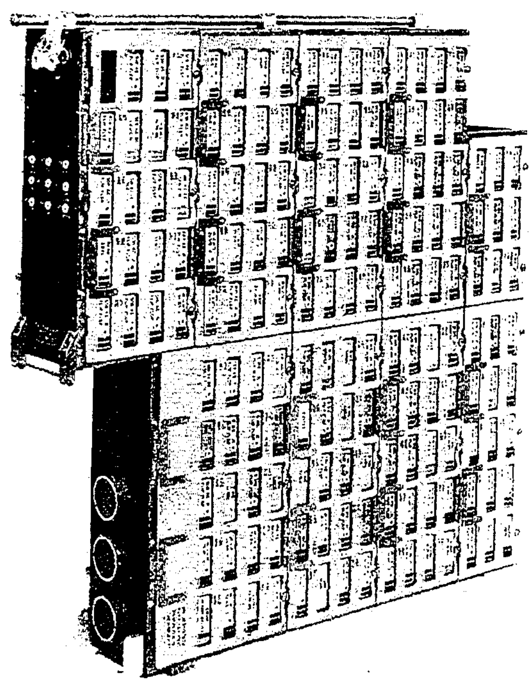

Fig. 2. Right-side view of pull-out frame showing accessibility to the minor test points on the modules and to the modules themselves.

4. Identical cable lengths for normal equipment operation or for maintenance. (Avoids patch or extender cable which mean undesirable operating time delays.)

The major test points are located on the upper face plate. Mounting feet on the lower front, a special bolt at the top extending from the front to the rear corner of the assembly, and a spring latch on the upper front of the frame (to stabilize any imbalance in the frame's center of gravity) provide the means for rigidly mounting the assembly into the computer. Two nylon-extruded angles are riveted to the bottom members of the frame assembly to aid in guiding and sliding the frame into and out of the computer.

BASIC FRAME CHASSIS

The frame fabrication itself features the LMED standard in frame construction. Figure 3 shows a typical sample of this construction from another piece of equipment. Seamless steel tubing (0.300 in.^{2}) is used in conjunction with special cast aluminum joint-forming fittings as the basic parts. The various joints are made by pressing the tubing onto the leg of the fitting and then upsetting or pressing the tubing into recesses in the leg. Because a dimpling tool is used with a pneumatic hand riveter, the dimpling is simultaneous on opposite sides of the tubing.

This unique method of frame construction offers tremendous assembly simplification over the older welded frame construction, which besides presenting manufacturing with distortion and finishing problems required special fixtures and jigs. This technique also makes it possible to assemble predrilled and finished members with an accuracy that guarantees assembly ease of subsequent component parts.

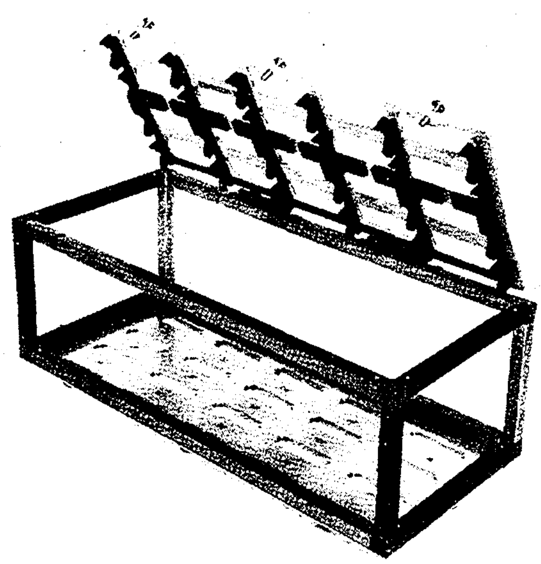

Fig. 3. Sample of the kind of frame construction used in the pull-out frames. Note the hold-down covers and their spring pad assemblies.

Panels and covers are attached to the framing with rivets or screws. Where screw threads are required, swaging and tapping of the wall has been found more than adequate.

PULL-OUT FRAME WIRING

In most computers the design and optimization of cable layouts provide some of the most challenging problems for the equipment designer. The wiring of the logic assemblies on this airborne computer was no exception to the rule. A special program, which releases design people from the tedious task of determining module location and writing the wiring lists for the factory wiremen, was designed for the Burroughs 220. With a listing of randomly placed modules and module interconnections as its input, the computer determined the optimum position for each module. The results of this optimization were further processed to obtain and print out on the wiring list format the correct sequence of wiring with routing into the appropriate coordinate channels on the mother plate. It also included such information as wire size, length, color codes, strip length, and other details to enable the factory wiremen to wire the assembly.

With the information from the computer program and the established LMED wiring standards, the wiring harnesses for the five pull-out frames were completely

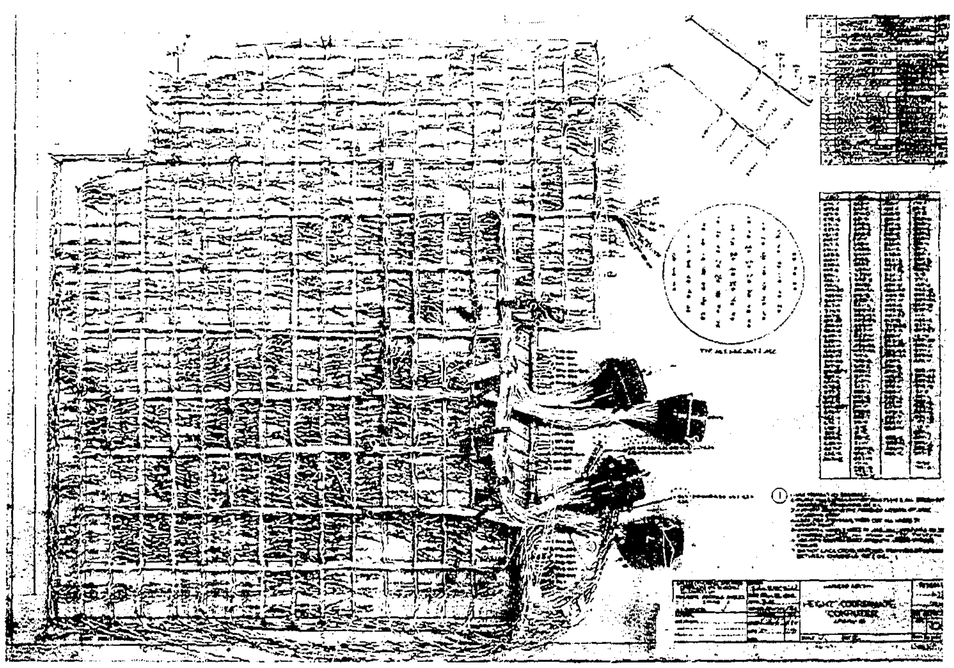

Fig. 4. Harness assembly mounted on cable board.

designed in Engineering. Full-scale drawings were made showing the developed lengths and the combined configuration of all wires in the harnesses. These were then released to Manufacturing along with all other drawings.

This added design responsibility in Engineering permits consistency in all cables and attention to such details as wire length, crossover build-up, and so on.

The use of engineered wire designs marks a significant advance in the design and manufacturing processes used in the Light Military Electronics Department. The design control so predominant in the mechanical design is now extended to the wire design as well. These designs also save many weeks in the manufacturing cycle and, at the same time, they guarantee superior quality and uniformity.

The time-saving is realized by revolutionizing the procedures used in developing equipment wire designs. The conventional method required that all electrical and mechanical parts be available and released to the manufacturing area before wire design effort could begin. Working from a wiring list and a connection diagram, the wire design men established routing, sequencing, clamping, lacing, etc. in wiring the first production unit. It was customary to remove this harness from the unit after wire checking and to use it as a guide in making up the cable board for the remaining production units. It is easy to see how delivery schedules became complicated with this series method of cable manufacturing.

With the wire design completed concurrently with the mechanical design, parallel fabrication, purchasing, and cable assembly are possible. Figure 4 is a photograph of the completed harness.

MODULE HOLD-DOWN

The motion of the circuit module under dynamic conditions is restrained by the hold-down covers shown in Fig. 3. The cover design, a practical application of fundamental beam theory, is based on flexing the materials involved to produce module restraint and, at the same time, compensating for tolerances between the module and the cover.

The hold-down assembly consists of a slightly concave plate to which are secured several module contacting elements and the spring-loaded pad assemblies. The hold-down assembly is hinged to the pull-out frame members, and quick access to modules is facilitated by loosening three captive screws. Access to the module test points is made easy by cutouts in the covers. The covers spanning four rows of modules are 0.090-in.-thick aluminum, while the covers which span three rows of plug-in assemblies are constructed of fiberglass cloth, reinforced epoxy resin. This latter material was selected because its modulus of elasticity ($\frac{1}{3}$ that of aluminum) permits the same module loading in a 3-in. span as the stiffer aluminum allows in a 4-in. span. The pad assemblies consist of a stainless steel spring preformed and heat-treated. Bonded to it are the molded plastic pads. These pads have molded-in recesses to guide any misaligned module to its proper position and to grasp the module at the "shoulder" of its extruded edges.

As shown in Fig. 5, the hold-down assembly is so designed that the center assemblies load the cover directly at the center of its span while the troublesome,

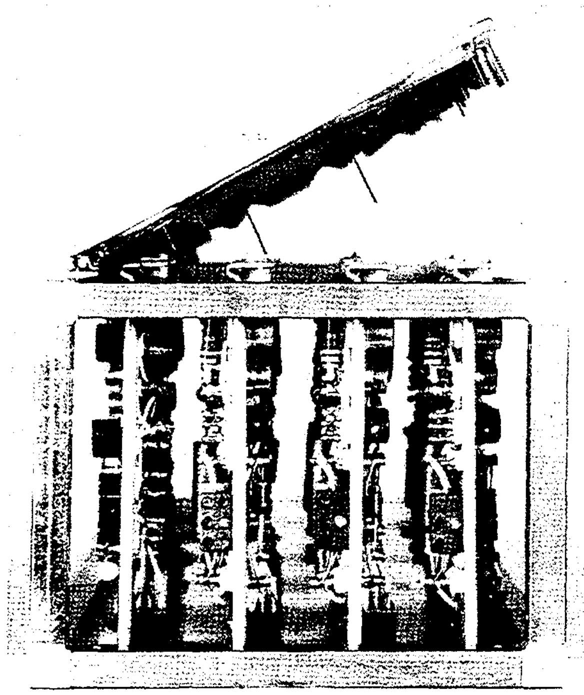

Fig. 5. Side view of a sample frame section with arrows illustrating module loading theory.

close-coupled outside assemblies distribute their loadings through the flex of cantilever beams. The beams, in turn, transfer these end loads to the center of the cover span. The loads on the ends do not exceed 2 lb. The loading of the control assemblies is a function of the tolerance between the cover and the module edges.

MAINTENANCE POSITION

The availability of a maintenance position feature in this equipment has proved to be as useful a tool for in-plant testing as it has been for field use. To mount a pull-out frame in its maintenance position (see Fig. 6) the following procedure is necessary:

1. The plugs on the lower front face of the pull-out frame are disconnected.
2. The spring latch is disengaged, and the upper and lower mounting hardware is unbolted.
3. The special lattice support is secured to the attaching fixtures on the front of the assembly. (The lattice is one of two supplied as special tooling with each equipment. All special tooling is stored on the internal surface of the upper cover.)
4. The assembly is then slid out of the computer, rotated 90° counterclockwise until the connectors are facing down. This will orient the hardware, which is on the lower rear of the assembly, so that it is even with a special

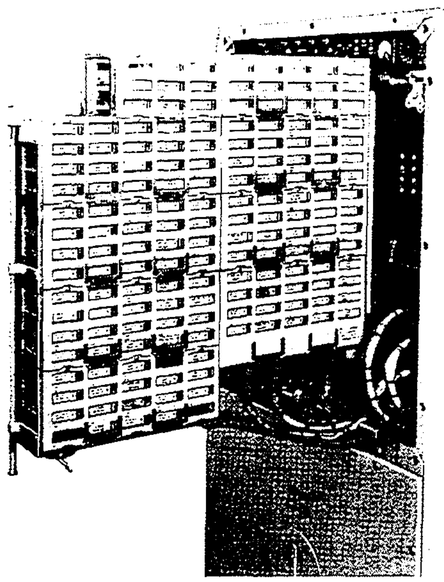

Fig. 6. Computer with the pull-out frame in its maintenance position.

stainless steel pin located on the maintenance panel of the equipment. The pull-out frame is slipped on and captivated on this pin.

5. The loose end of the lattice support is then forced into slots on the main assembly, completing the mechanical support of the pull-out frame.
6. The cables are reconnected to the pull-out frame.

MODULE DESIGN

The evolution of the computer circuit module followed closely the development of the overall computer packaging concept. Determination of the packaging outline for the logic section was made only after space allotments had been made for each of the other ARA's. With a fixed volume to work in, logic changes requiring increased numbers of modules meant a gradual but definite reduction in the allowable module size. What had started out to be a 250-module computer had now grown with the increased functional requirements to one requiring 700. In order to allow approximately 16% for future growth, the complement possibility was set at 815 modules.

A point-to-point wired assembly won out over other packaging techniques as the standard computer module because of its outstanding advantages in reliability, repairability, cost, and volume. In addition, it had these features:

1. Withstands, without exception, MIL-E-5400B environmental conditions: shock vibration, humidity, etc.

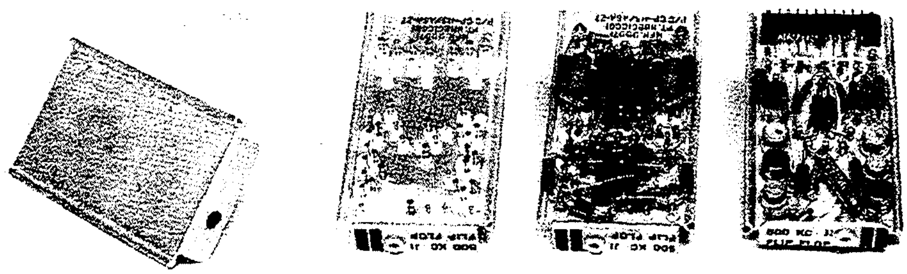

Fig. 7. Point-to-point wired module, which was the standard assembly during development.

2. The number of soldered joints is reduced because multiple wiring can be used at each terminal.
3. Conventional soldering techniques on a progressive assembly line are possible.
4. Design and labor costs are comparable to or cheaper than other techniques.
5. Finally, and most important of all, there is flexibility in the incorporation of design changes during the developmental phase.

The basic component mounting plate is an aluminum extrusion, shown in Fig. 7. The edges are designed to interlock, providing stiffness to the assembly and guiding the module into the connector. The postformed lip at the top of the module functions as a finger grip as well as a mount for individual test points. A strip identifying the module by name and code is bonded to the top surface of the lip.

Modules are wired by using tetrafluoroethylene standoffs, feedthroughs, etc. Special transistor mounts, with wiring terminals, were introduced on the module design making it possible to reduce the number of terminals required on any assembly.

The connector used is a 29-pin arrangement which offers in a subminiature size the advantages of larger pins and contacts available in the miniature connector size. The pin is 0.040 in. in diameter, and the contact is a special four-leaf beryllium copper configuration. Guide pins, receptacles, and hardware are made of stainless steel. The molded body is of diallyl phthalate.

The weight of any one of the 60 different types of circuit modules averages 2 oz. Packing densities on the individual assemblies vary through the range of 10.5 to 14.7 *standard* components per cubic inch. These components (making up a complete circuit in every case) are assembled within the 3.4 × 1.9 in. standard area available on the module form.

PRODUCTION DESIGNED MODULE

For the advanced or production design of the computer, another version of the module has been developed which meets all of the functional requirements of the development assembly and in addition employs the latest Department packaging techniques. This design is shown in Fig. 8. All interwiring is accomplished by an LMED-standard welded wire matrix.

These connections are composed of transverse and longitudinal wires welded at the appropriate intersections. The transverse wires terminate (by welding) to terminal rails which are the brass forms for mounting components.

After the matrix is prepared, it is imbedded in an encapsulant which supports the welded connections and rigidizes the component mounting rails. After it is cured, the matrix assembly is bonded to the standard module form, which in this case is a diallyl phthalate molded part.

Because this module design features components mounted on both sides of the molded form, two matrices are used for each circuit. Interconnections between them are made by welding the common extended wires together at the lip end of the form. Connections to the connector are made by soldering the matrix extended wires. Component connections to the terminal rails are also soldered.

CONCLUSION

Confronted by an airborne environment with its space and weight limitations, its extremes in ambient conditions, and the associated severe reliability and maintainability requirements, the product designer of electronic equipment is faced

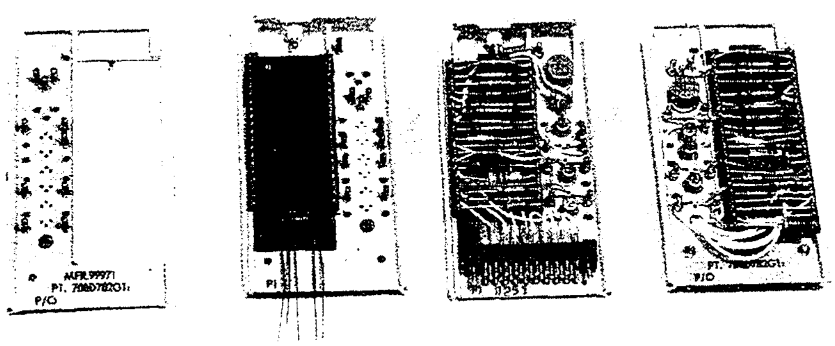

Fig. 8. Welded wire matrix version now used in production equipment.

with a formidable task. His solution to these problems can ultimately lead to greater equipment efficiency and, of course, to significantly less aircraft down-time.

This airborne computer has been made a more effective segment of the aircraft's electronic complex by endowing it with a practicable design, completely oriented toward ease of maintainability.

DISCUSSION

Q. (Murray Lehrer, Sperry Gyroscope, L. I., N. Y.) Concerning interconnection between modules, did you consider any other form of interconnection, such as taper pins?

A. We considered tape or flexible wiring. We found that where we wanted direct interchangeability, flexible wiring was not competitive with conventional wiring techniques. This was true whether we considered the pull-out frame wiring (complex but small quantity) or the wiring on the module used in large quantity (300 per equipment). Inability to hold close tolerances on large sheets (20 × 20 in.) also discouraged its use.

Q. Did you ever use taper pins, considering the close proximity of the points to be wired?

A. Our concern was only this—we had five pull-out frames and something like 0.56-in. dimension between frames that could be allowed for wiring. If we used taper pins this dimension was exceeded, and the frames would not fit into the equipment.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) I would like to compliment you, Lou, on a very fine paper. I would like to ask you to comment on the use of the term "standard" as you used it in your paper because of a rather personal interest in the subject on my part. You mentioned that the welded-wire matrix and the tubing construction are standards or design standards in your company. Would you care to indicate briefly how these are developed and what the relationship is between those who develop these standards and those in the engineering assignments who utilize them?

A. In our department, we have an engineering standards group whose function is to provide engineering with some basic tools and guides to be used in equipment designs. The standards constitute approved controls applied to those parts, materials, design practices and techniques involving manufacturing processes used in the design, fabrication, and assembly of our department's products. These standards are established by selection and/or development of design information by our standards group.

The source of design information may come from our advanced design or from individual product line design groups. In the case of the frame construction, technique development was within the product line long before any formal standards group existed. This technique freed us from the problems of fixturing, warping, and entrapment of fluids associated with welded frames which had been conventional with us. You can imagine that it won quick acceptance from both manufacturing and engineering.

Advanced packaging techniques such as the welded-wire matrix are the responsibility of the Advanced Product Design unit. Such techniques or designs are integrated with the manufacturing group prior to acceptance or publication as a department standard.

As mentioned before this standard means that sufficient design details coincident with manufacturing capability are established to guarantee reproducibility within department acceptable quality standards.

These techniques and processes are the ones that engineers are encouraged to use in their designs. There is some good logic in limiting, but not discouraging, development of new packaging techniques. The manufacturing organization cannot accommodate 18,000 different processes at the same time and be competitive. It is left to the engineer to evaluate those existing techniques with regard to the various common factors applicable to the equipment being designed to see which, if any, are usable.

At the time of this design, our standards people were pressing us to use welded-wire matrix or printed wiring. I argued, successfully, for the point-to-point wired assembly on the basis that no process was perfected in the department to handle this module size.

Q. (Al Acken, RCA, Van Nuys, Calif.) I would like to know how you established the size of the particular module that you used so that you had enough space to get the components for your highest-density package and still have good utilization for your other modules?

A. I forgot to say that the pull-out frame outline was a culmination of many outlines which changed as fast as the logic designers' estimate of the number of building blocks required. In fact, we even considered the rotating shelf outline à la the GE refrigerator. A quarter-circle segment was built for laboratory use, but when module quantities exceeded 650, it had to be abandoned for use in this equipment. Knowing that we only had $10\frac{1}{2}$ ft^3 to work in, volume estimates were made of all subassemblies in order to establish the maximum volume which could be assigned to the logic assemblies. We arbitrarily established that the number of logic frames in this remaining volume would be five. Utilizing the logic designers' estimate of numbers was proved by layout and assembly of several of the modules used in large quantities and with large component count.

Q. (Walt Luebking, ITT Kellogg, Ft. Wayne, Ind.) You mentioned that your wiring harnesses were laid out by the engineering department. I would like to ask what kind, or what classification, of personnel you use in this operation?

A. Our design drafting people do this with, of course, direction from the engineers. The design wireman is given the logic diagram and he is told which wires are critical. In this particular design we actually programmed a Burroughs 220, which told the wire design draftsman where the position of each module was in that particular assembly. He proceeded from there.

Q. (Laurence L. Slick, Magnavox Co., Ft. Wayne, Ind.) The standard airborne environmental spec calls for an overall equipment to pass $10g$'s vibrations at 500 cycles and 15 and $30g$ shock. Does this equipment pass that or was there a deviation given?

A. No, this equipment is currently in preproduction testing and is designed to meet MIL-E-5400 B environment.

Q. (Gene DesJardin, Kaiser Aircraft, Palo Alto, Calif.) How many of these computers are you making?

A. How many have we made?

Q. How many do you plan on making? The reason I am asking is it might be maintainable, but it looked like it would be a little bit difficult to reproduce.

A. It is not difficult to reproduce at all.

Q. Well, economically, let us say. I agree you probably can't get a flexcable to fit that, but possibly something a little more stable. There is a lot of hand work in the module that you are going to produce in quantity—you can't adapt that to machine operation at all.

A. Let us face it; the wiring on this equipment is complex. By rigidly controlling the wire design we have succeeded in reducing the difficult assembly task to an orderly and orthodox procedure. Our manufacturing people are as critical of engineering as I am sure your manufacturing people are. When we proposed early conversion of our module to the welded-wire matrix, it met with a lukewarm reception from manufacturing because of the low assembly cost which had been achieved with the present design. We have built over ten equipments already.

Q. (Jack Dune, Cinch Mfg. Co., L.A., Calif.) I kind of had the feeling that printed circuit boards look as if they are not here to stay. Your printed wiring state of the art today seems to have been upgraded by the advent of point-to-point wiring, and I am wondering if in future larger-volume production you will be going in this direction as other module manufacturers have?

A. Definitely not. If we were going to go to any other technique it would be the welded-wire matrix.

Q. One other question with regard to termination into the connectors. Did you consider a crimp snap-in type of removable connection into the body of your connector for maintaining a quick interchangeability of connectors with your wire?

A. No, we didn't consider that at all. I would like to say with regard to printed wiring, I did a lot of work in printed wiring years ago and I would say this: 50% of the time our engineers were not trying to find out if their circuit designs were good or if the system worked; they were trying to find a cold solder joint, an open wire, that sort of thing. We have yet to find a cold solder joint in three years on the point-to-point type of module.

Q. (Dick Snow, Hughes Aircraft Co., Culver City, Calif.) I would like to ask what the insulation on the wire is in the harness?

A. On the wire on the pull-out frame? It is a nylon jacket over polyvinyl chloride.

Q. How was the maintainability of that harness considered in your design or in this paper? It appears to me that it is very difficult to get a soldering iron in there to make a change on the harness although you might be able to change the rest of it without burning it up?

A. It does appear to be a difficult job, but our manufacturing people are very well trained to do it. And I know that the Grumman people are doing this right now, i.e., when we put out a field change.

Q. (Joe Ritter, Electronic Modules Corporation, Timonium, Md.) It seems to me that you have been so interested in maintainability of this equipment that you designed in all the things that are going to make you maintain it. It is true that there have been a lot of processes that there have been troubles with in the past, and years ago we had a lot of troubles with a lot of things, but a lot of these processes have been improved. It also seems to me that, this being an airborne equipment, even though you are concerned about weight, you have put a lot of heavy metal into it; on the printed circuit boards I believe you had some metal—either castings or sheet metal backup for them. Your clock rate is only 500 kc. I doubt that this was for shielding purposes. The whole thing looks like the weight could be cut approximately in half, and it could be made a lot cheaper by using some of the newer techniques that have been proven.

A. Far be it for me to say it couldn't be designed more cheaply. If we had another crack at it, we would use many of the newer techniques also. As far as your comment about weight, there was a specification placed on weight and we are within that spec. Weight reduction studies have been made and best estimates indicate that a weight saving of 45 lb is possible.

Q. (Al Painter, Bendix Computer, L.A., Calif.) Did you say that your arithmetic was at 5 Mc?

A. There are some 5-Mc circuits in this, yes.

Q. What type of logic are you using and how many functions to the module?

A. We have diode and/or logic.

Q. How many functions to the module?

A. The number of functions varies from one type to another. This number can be from 1 to 8 per module.

micro module
printed circuits

Digital Micromodular Equipment (MICROPAC) Design Concepts

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The feasibility of micromodule circuitry packaging in tactical digital equipment has been demonstrated by the design, fabrication, and test of MICROPAC (*Micro*module Digital Processor And Computer). As a by-product of the MICROPAC program, equipment design techniques for the economical mounting and interconnection of and heat transfer from digital micromodules have been developed and are described herein. It is shown that the circuitry booklet technique of micromodule mounting and interconnection lends itself to efficient heat transfer by forced air cooling, provides for a high packaging density, and permits micromodule interconnection wiring without multilayer wiring. Techniques for the assembly, wiring, and maintenance of high-density digital micromodule equipment have also been developed and are described herein. Finally, it is shown how the 1958 concept of the micromodule as a technique for packaging individual electronic components is advancing toward the 1962 concept of the micromodule as a technique for packaging multiple integrated electronic or solid circuits. The mixture of both concepts or techniques in future militarized digital equipment offers the promise of completely micromodularized digital equipment of high-speed performance, high reliability, and small size at fabrication costs substantially less than those for currently available conventionally packaged digital equipments.

INTRODUCTION

MICROPAC IS THE acronym applied to the *Micromodule Digital Data Processor and Computer* selected by the U.S. Army Signal Corps as the equipment vehicle for demonstrating the feasibility of micromodule circuitry packaging in tactical digital equipment. It is the purpose of this paper to describe the digital micromodular equipment design techniques which have been developed by RCA under the MICROPAC tasks of the U.S. Army Signal Corps Contract No. DA-36-039-SC-75968 for the Micromodule Production Program.

The micromodule is a form of electronic circuitry packaging wherein a stack of thin, uniformly shaped, waferlike components is interconnected by means of twelve wires attached around the periphery and encapsulated to form a rugged, compact module (see Fig. 1). The micromodule is 0.36 in.^{2} and varies in height according to the circuitry content. The essence of the concept (as visualized in 1958 when the program was initiated by the Signal Corps) is a standardized assembly of electronic components in accordance with a disciplined geometry. All components employed within the micromodule are required to satisfy and are tested in accordance with rigid, compatible specifications. Furthermore, production equipment and processes have been and are being established to provide for simple mechanization of component fabrication and assembly with complete flexibility for inclusion of any desired complement of active and passive components.

As the program has progressed, and as electronic component and semiconductor technology have advanced, it has become feasible to mount many components on a single wafer and to incorporate integrated semiconductor networks or circuits within the micromodule. The latest available digital high-speed micromodules do incorporate such networks within the module package.

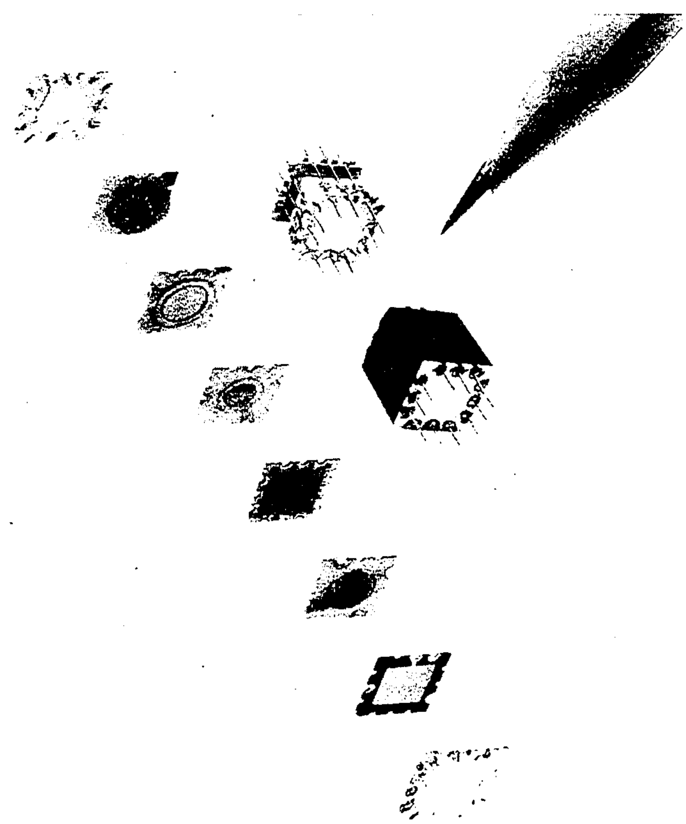


Fig. 1. Micromodule circuitry packaging concept.

MICROPAC is a general-purpose, militarized digital computer designed for tactical applications where high reliability, small size and weight, and low power requirements are of major importance. It is a binary synchronous computer operating in a completely serial mode at a clock frequency of 1.6 Mc. It possesses a basic random-access ferrite core memory of 2048 words expandable in multiples of 2048 words to a maximum of 8192 words. Twenty-one FIELDATA instructions are mechanized with operating speeds of approximately 80 μs for arithmetic and transfer instructions and 1000 μs for multiplication and division of 36-bit words. Three types of input–output are provided, namely, via the control panel, paper tape reader and punch, and via a full-duplex, real-time communication channel. MICROPAC is required to operate under military service conditions, listed in Table I.

Shortly after the initiation of the MICROPAC program in February 1960, a full-scale mock-up was fabricated and is shown in Figs. 2 and 3. Complete with transit case, MICROPAC was estimated to weigh approximately 100 lb and to occupy approximately 2.5 ft^3 in volume. MICROPAC was visualized as comprising four major sections: control panel, circuitry (logic and memory), memory, and power supply. Upon completion of the logic, circuitry, and memory design, it was estimated that approximately 1200 logic and 400 memory micromodules (a total of 1600 micromodules) would be required for a 2048-word MICROPAC. Space was provided for two 2048-word memory units plus associated addressing and drive circuitry. It was estimated that the power supply would be required to furnish 250 w dc (150 w for logic and 100 w for memory circuitry) and 40 w at 400 cps for the circuitry and power supply cooling fans.

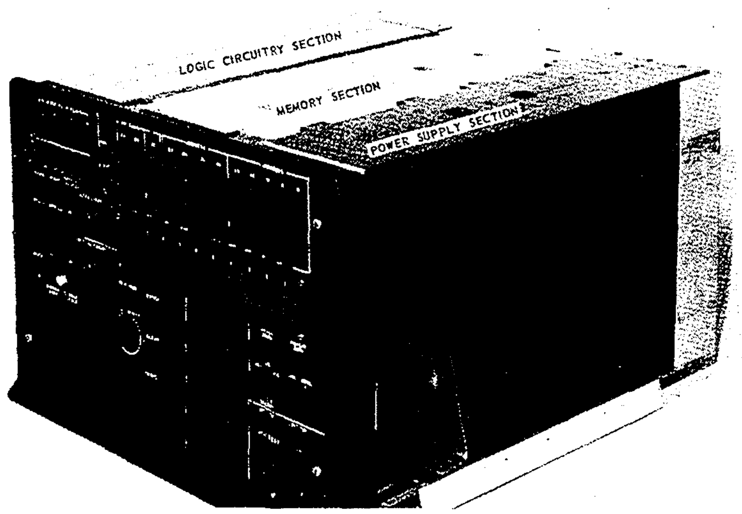


Fig. 2. MICROPAC computer mock-up (Assembled).

TABLE I

Military Service Conditions Required for MICROPAC

	OPERATING SPECIFICATIONS
Temperature range	$-0.25°$ to $+125°F$
Relative humidity	98% to 100% exposure for 4 hr
Rain test	Rain in 25 mph wind at 2-in. rate
Elevation	8000 ft above sea level
Dust proof	25 mph wind 0.5 g/ft^3
Orientation	20° from normal operating position
	NONOPERATING
Temperature	$-80°$ to $+160°F$
Relative humidity	98% indefinite period; 100% with condensation 4 hr
	GENERAL SPECIFICATIONS
Immersion	3 ft of fresh water for 2 hr
Vibration	10—55 cycles at 0.0156-in. excursion rate
Shock test	4—30° drops on each edge 26—2-ft drop tests on 2-in. fir with concrete base
	APPLICABLE MIL SPECS
MIL-STD-169	Temperature test
MIL-STD-170	Humidity test cycle for ground signal equipment
MIL-STD-202	Test methods for electronic and electrical component parts
MIL-STD-252	Wired equipment, classification of visual and mechanical defects
MIL-I-11748	Interference reduction for electrical and electronic equipment
MIL-M-13231	Marking of electronic items
MIL-F-14072	Finished for ground signal equipment
SCL-6200	Parts, materials, and processes used in electronic communications equipment
SCL-4249	Performance specification for MICROPAC
SCL-1280A	Configuration and installation of electronic and associated equipment in vehicles and shelters
SCL-1787	Human factors engineering for Signal Corps systems and equipment
SCL-1935	Voice communication terminal for data processing
SCL-1939	High-speed digital data terminal
SCL-6250B	Ultraminiature connector
MIL-STD-415	Test points and test facilities, design standard for
MIL-STD-441	Reliability of military electronic equipment
MIL-STD-189	Rack, electrical equipment, 19 in. and associated panels

The primary objectives of the MICROPAC program were as follows:

1. Demonstrate the feasibility of micromodule circuitry packaging by the design, fabrication, and test under military environmental conditions of a completely operative tactical digital computer.
2. Provide to equipment designers proven, general-purpose, current state-of-the-art equipment design techniques for the mounting, interconnection, and heat transfer of digital micromodules.

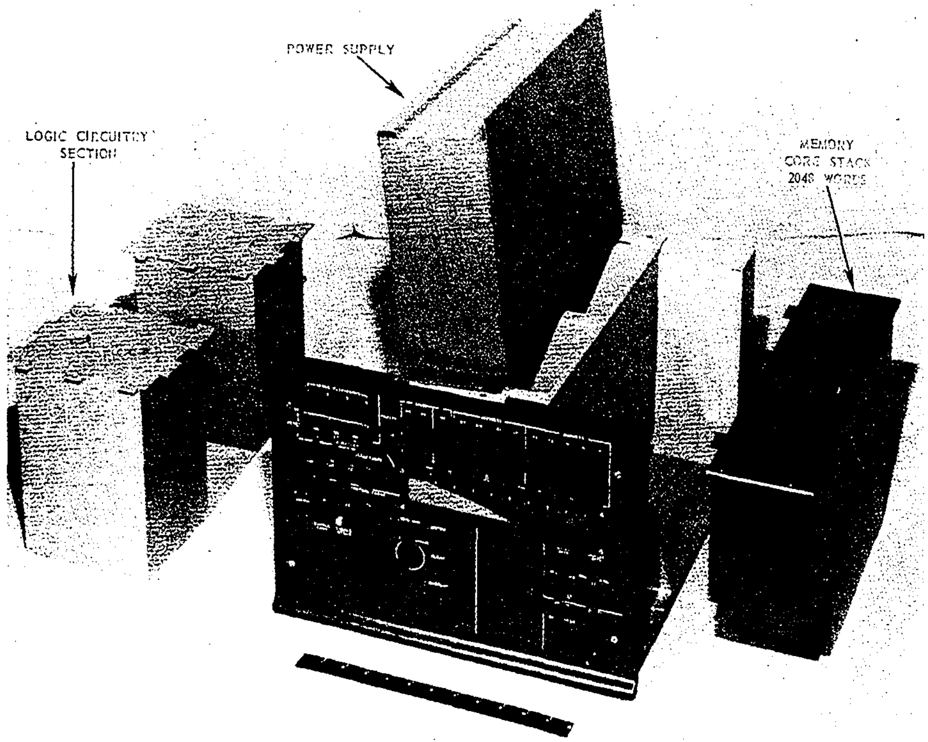


Fig. 3. MICROPAC computer mock-up (Disassembled).

3. Demonstrate the degree of compatibility of the micromodule concept of circuitry packaging with the latest and future techniques of integrated electronic circuitry.

In describing the MICROPAC design concepts, emphasis will be placed upon digital circuitry packaging at four levels of circuitry mounting and interconnection as follows:

1. *Circuit level*—wherein one or more circuits are packaged in a micromodule. The micromodule is the minimum "throwaway" unit.
2. *Card level*—wherein a number of circuit micromodules are mounted and interconnected to form a plug-in card or booklet. This card is usually the basic replaceable item in field maintenance at first and second supply echelons.
3. *Subsection level*—wherein a substantial number of plug-in cards or booklets are mounted and interconnected by a common backplane. Wherever possible, the resulting subassembly should be a functional unit (of the complete system) which can be fabricated, assembled, and tested

separately. This level is the maximum level reached in the MICROPAC computer.

4. *Section level*—wherein a number of subsections are mounted and interconnected together via a common backplane. This level would be reached in larger-scale, more complex computers or digital equipments.

The design concepts employed at each level will be described from the viewpoint of illustrating to what extent the previously described objectives have been or will be met.

CIRCUIT LEVEL PACKAGING (MICROMODULE)

As previously mentioned, the basic circuit package and building block of the MICROPAC computer is the micromodule. Each micromodule contains two logic gates or one flip-flop or equivalent. Diode clusters and one to two ferrite core memory circuits are also incorporated within a micromodule to provide an average of 1.6 circuits per micromodule for the complete MICROPAC computer. All logic and memory circuits are packaged in micromodules.

Silicon diode-transistor logic circuitry is employed in MICROPAC. The circuits are designed and tested using conventionally packaged components. A micromodule layout, such as shown in Fig. 4, is then prepared by the design engineer to provide the basis for the fabrication of prototype micromodules. Upon successful completion of prototype test and evaluation, specifications are released for production of final micromodules.

The height of the MICROPAC micromodules would vary from 0.450 to 0.700 in. as a function of circuit content. In order to improve the effectiveness of heat transfer and to simplify fabrication, assembly, and test, it was decided to employ a micromodule with a fixed height of 0.7 in. in MICROPAC. Twelve leads or pins are brought out from the base for interconnection to a printed-wire card or board; usually, three or four leads are used for dc power and ground, thereby providing eight logical connections to be divided between two circuits. The micromodule will be dip-soldered into a printed circuit card during production and may be readily removed and replaced by micromodule soldering irons provided for the purpose.

A detailed description of the micromodule concept, microelement availability, digital micromodule reliability and cost, production fabrication, and program and current manufacturing processes is contained in an RCA document, entitled *The Micromodule Program—A Status Report*. This document indicates that the following characteristics of the micromodule circuit packaging have been achieved as a result of the 4-year, $20,000,000 continuing program sponsored by the Signal Corps.

- *Reliability*

  Accelerated-life test data for microelements and micromodules indicate failure rates comparable to the expected goals for Minuteman high-reliability components. Current life test data indicate a mean-time-between-failures (MTBF)

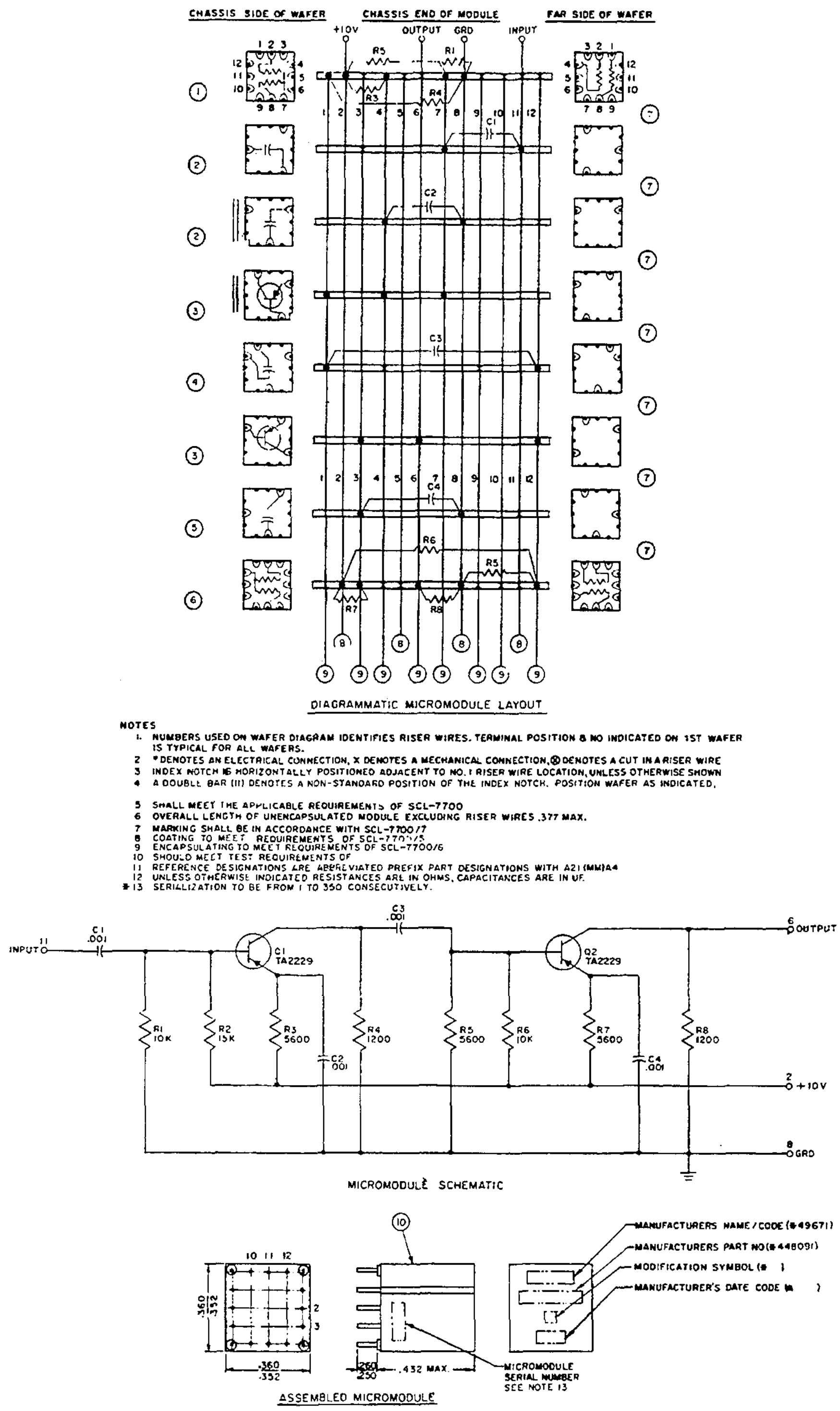


Fig. 4. Typical micromodule layout sheet.

of more than seven million hours for a 15-part MICROPAC micromodule under equipment operating conditions. The reliability goal for a module composed of Minuteman high-reliability components would be eight million hours. It may reasonably be anticipated that the Minuteman reliability goal will be achieved by micromodule packages as a direct result of the continuing micromodule reliability program.

- *Competitive Cost*
  Cost analysis and micromodule quotations indicate that silicon logic and memory micromodules can be obtained in quantity production (25 computers or more) in 1964 at an average price of \$15.15 per logic micromodule and \$26.50 per memory micromodule. These prices are approximately 4% and 30% greater than those obtained for equivalent logic and memory cordwood modules, composed of standard military components and $\frac{1}{5}$ as much as obtained for cordwood modules composed of Minuteman high-reliability components.

- *Production Capability*
  As a direct result of the \$6,500,000 production engineering and facilitation phase of the micromodule program, a minimum capability of 25,000 modules per month from each of three suppliers (RCA, Mallory, and Paktron) will be available in early 1963.

CARD LEVEL PACKAGING (CIRCUITRY BOOKLET)

After the establishment of module types, quantities, heights, power dissipation, etc., it is necessary to devise an efficient and effective means for mounting, interconnecting, and cooling these modules within the volume allocated to the micromodule circuitry section in the overall MICROPAC equipment (see Fig. 3). The circuitry section is approximately 10 in. high × 5.5 in. wide × 14.5 in. deep. The height of each MICROPAC section is fixed by the minimum allowable height for the control panel. The width of the equipment is determined by the requirement for rack mounting and is therefore approximately 17 in. Each of the three major sections were allocated approximately one-third of the area of 5.5 in. The depth is adjustable up to a maximum of 24 in. less control panel, cooling fans, and external cable allowances.

In order to meet the requirements for mounting, cooling, and interconnection of the required modules with maximum packaging density and in a manner consistent with field maintainability, it was decided to utilize the concept of a circuitry booklet (see Figs. 5 and 6). The booklet consists of two printed cards, mechanically and (in some cases) electrically interconnected, with modules mounted on each card and sandwiched between them. Alternate rows of modules are positioned so that two sides will be parallel to the flow of cooling air. Minimum space (0.10 in.) between modules is allocated in a direction parallel to air flow. Each card contains a connector to permit removal of the entire booklet.

The circuitry booklet represents an evolutionary step beyond current printed

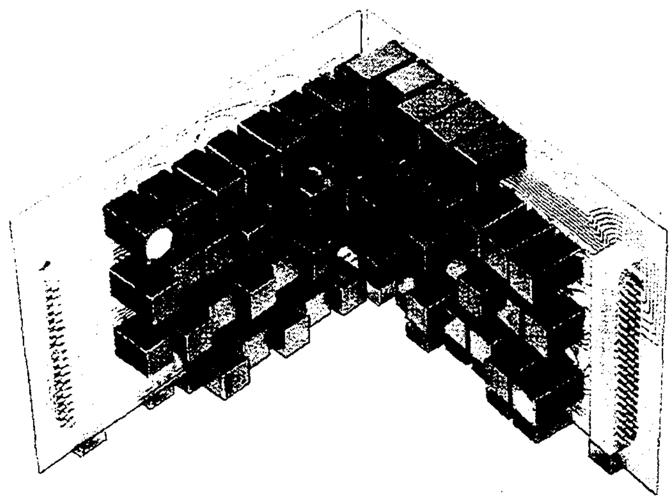


Fig. 5. Circuitry booklet (interior view).

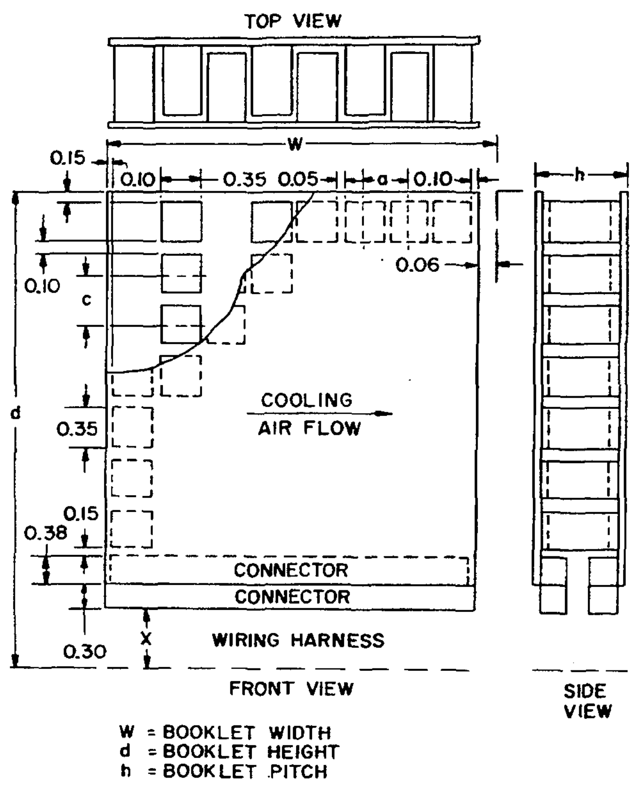


Fig. 6. Micromodule circuitry booklet.

card mounting techniques in use for militarized equipment. It offers the following significant advantages:

1. Provides wiring space between modules.
2. Doubles the ratio of connector pins to modules.
3. Channels flow of cooling air to provide efficient heat transfer.
4. Increases rigidity and strength of module mounting.
5. Provides above advantages at minimum loss of packaging density.

In the following paragraphs, the heat transfer and interconnection characteristics of the circuitry booklet are described.

CARD/BOOKLET CONFIGURATION

The determination of the optimum card/booklet configuration; i.e., micromodules per card, card height and width in terms of micromodules, and number of connector pins per card, results from the necessity to satisfy several conflicting requirements as follows:

- *Interconnection Requirements*
  To provide the necessary number of connector pins per card or booklet for satisfactory implementation of the logic design—although this problem is encountered in the design of digital packages of conventional form and size, it becomes particularly acute when the circuit packaging density increases substantially.
- *Field Maintenance and Logistics Support*
  To minimize the field maintenance and logistics support cost of digital equipment by the selection of a card size which lends itself to standardization.
- *Minimum Size and Weight*
  To maximize the circuitry packaging density in a manner consistent with the above described requirements.

In the design of the MICROPAC computer, every effort was made to establish these requirements in quantitative terms. The determination of card connector-pin requirements per module as a function of card or booklet size (in terms of micromodules) was made by partitioning selected samples of the MICROPAC logical design into circuitry booklets of several different sizes. The results of this analysis are shown graphically in the curve of Fig. 7 wherein maximum connector-pin requirements per module are plotted *vs* booklet size for two types of logic implementation, namely, logic-on-card and universal logic. In universal logic card packaging, all logic inputs and outputs are brought to the connector, i.e., as few interconnections as possible are made between the basic logical elements. In logic-on-card packaging, the basic logic elements are interconnected upon the card in order to minimize the number of connector pins per logic element. Thus, in logic-on-card packaging, as the module size of the booklet increases, more logical interconnections can be made upon the card and the number of connector pins per

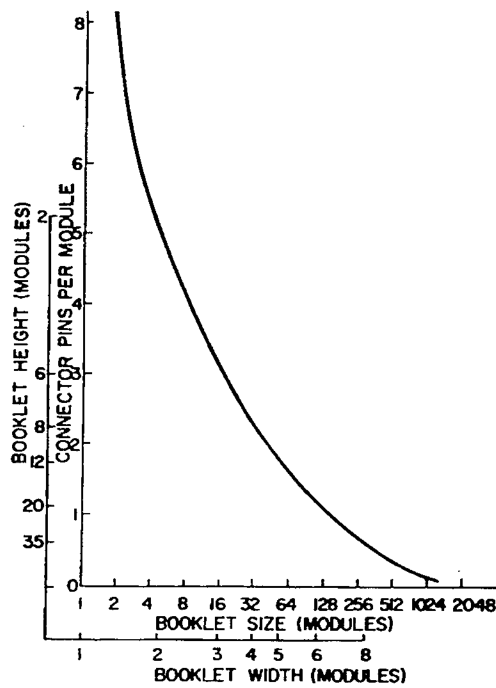
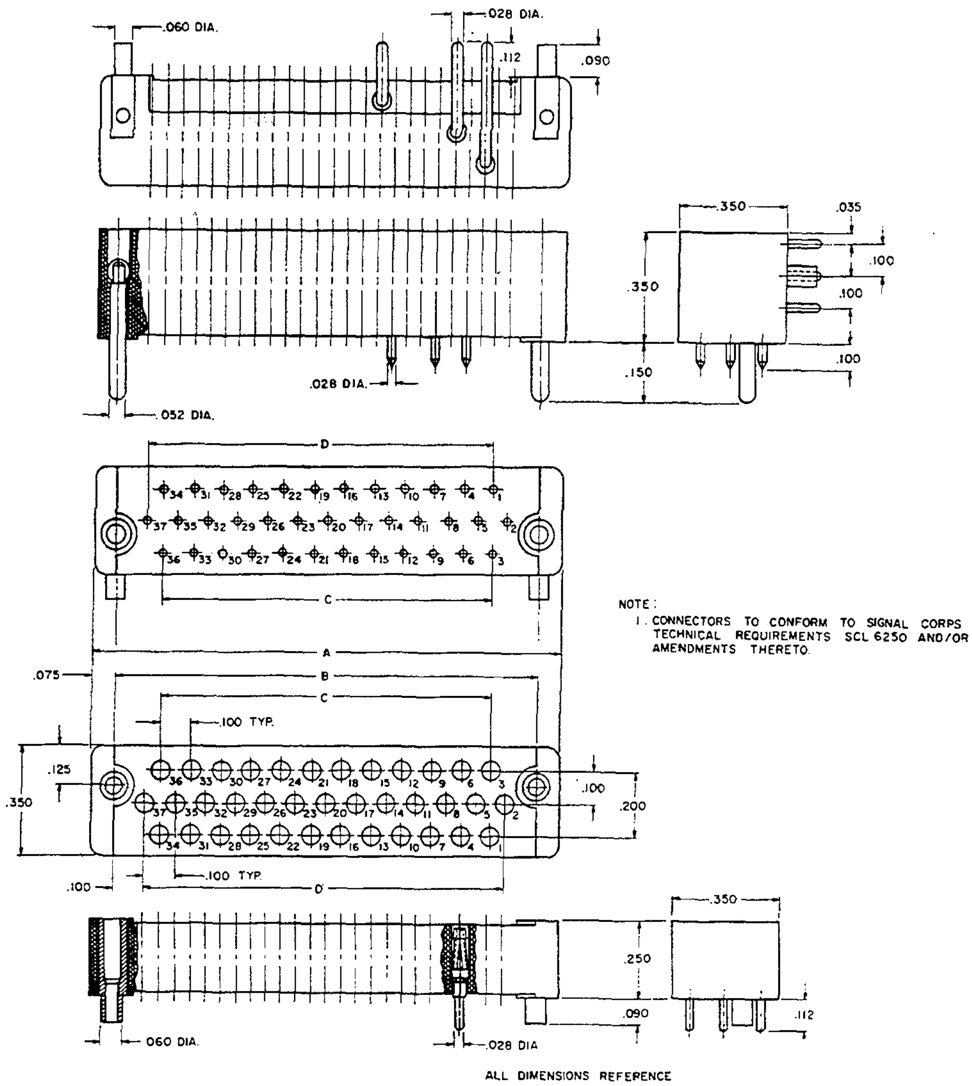


Fig. 7. Micromodule card connector-pin requirements per module.

module decreases. If all modules are placed upon a single card, the only connections required are for signal, clock, and power input and output (a total of approximately 30) for about 1600 modules, or a connector-pin per module requirement of approximately 0.02. At the other extreme is the condition wherein each micromodule is plugged into a backplane so that 12 pins per module are required.

The next step in the path toward selection of the micromodule card configuration was to obtain an expression for the packaging density of the circuitry booklet (including connector and backplane wiring volume) as a function of booklet size. Such an expression should take into account for the connector-pin requirements shown in Fig. 7 and the connector-pin availability from a specific card connector. In order to optimize the packaging density of the overall circuitry section, two of these connectors should be capable of mounting between the cards of a circuitry booklet. Each connector should possess a high pin density compatible with the increased circuitry packaging density. A 61-pin connector which meets these requirements has been developed by the Burndy Corporation for the Signal Corps, and is illustrated in Fig. 8. With this connector, a booklet pitch (center-to-center distance) of approximately 0.95 in. can be obtained with printed cards. With use of the known characteristics of this connector (approximately 26 pins per linear inch) in conjunction with the connector-pin requirements shown in Fig. 7, an analytical expression was developed for booklet packaging density and is shown graphically in Fig. 9. This curve indicates the desirability of selecting a large booklet size in order to achieve maximum packaging density. However, if too large a booklet size



DASH No.	No. OF PINS	"A" DIM.	"B" DIM.	"C" DIM.	"D" DIM.
1	13	.750	.600	.300	.400
2	25	1.150	1.000	.700	.800
3	37	1.550	1.400	1.100	1.200
4	49	1.950	1.800	1.500	1.600
5	61	2.350	2.200	1.900	2.000

WIDTH OF CARD IN MICROMODULES	LENGTH OF CONNECTOR	CONNECTOR DASH NUMBER	No. OF CONNECTOR PINS
2	.8"	-1	13
3	1.2	-2	25
4	1.6	-3	37
5	2.0	-4	49
6	2.4	-5	61
7 AND UP	TOOLING DOES NOT EXIST FOR LARGER CONNECTORS		

Fig. 8. MICROPAC card connector.

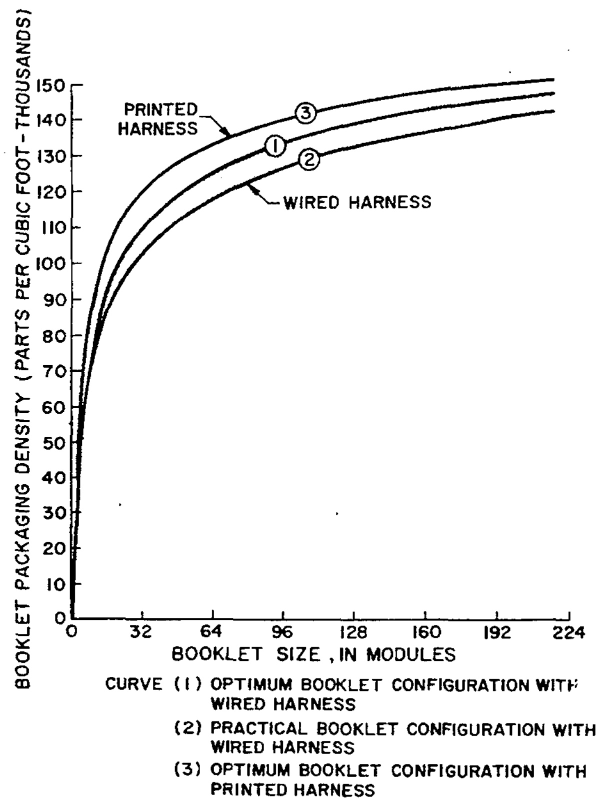


Fig. 9. Booklet packaging density *vs* booklet size.

is selected, the cost of logistic support via spare parts may be greatly increased; moreover, the field maintenance and repair cost will also be increased since it will be more difficult to locate a defective module on a larger card. A compromise was therefore made between packaging density and field maintenance and logistic support considerations by the selection of a card size corresponding to the knee of the packaging density curve, namely, 64 micromodules per booklet or 32 micromodules per card. The length and width of the booklet was chosen as eight modules subject to the considerations involved in the determination of the overall circuitry section. With a 61-pin connector on each card, a minimum of two connector pins per micromodule is available for implementation of the logical design.

MICROMODULE BOOKLET HEAT TRANSFER

To obtain experimental heat transfer data for the micromodule circuitry booklet, thermal test micromodules were fabricated by potting epoxy blocks around an internal $\frac{1}{2}$-w resistor, with a copper plate mounted externally on one side. Thermocouples were connected to the copper plates of modules located at various depths with respect to the direction of air flow in order to measure module surface temperatures. The intermodule spacings on each card of the booklet were the same as shown in Fig. 6. Inlet and outlet diffusers were connected to an assembly of several booklets, 24 modules in depth, so as to direct metered ambient air over the module surfaces. Resistors in each module were connected to a common power bus and the supply voltage varied to obtain different values of module power dissipation. Thermocouple leads were brought out for measurement of the module surface temperature as a function of module depth with rate of air flow as a parameter. Tests were conducted for two module configurations on a card (in-line and diagonal) and for various relative positions of modules with respect to the direction of air flow. Tests were repeated at power dissipations per module of 100, 200, 350, 500, and 650 mw.

Turbulent air flow was obtained at all values of air flow from 0.004 to 0.010 lb/min per total watts dissipated for the in-line module configuration, as shown in Fig. 6. The pressure drop was measured and found to be less than 0.5 in. (water) for all values of air flow. This drop is well within the capacity of currently available axial-vane fans.

The experimentally derived data were carefully analyzed in order to provide a solid foundation for the design of future digital micromodule equipment. The results of this analysis are shown in Figs. 10 and 11.

Figure 10 is a graph of maximum micromodule surface temperature rise *vs* cooling air flow (in cubic feet per minute) with average micromodule power dissipation as a parameter. This graph is applicable to a circuitry section (similar to

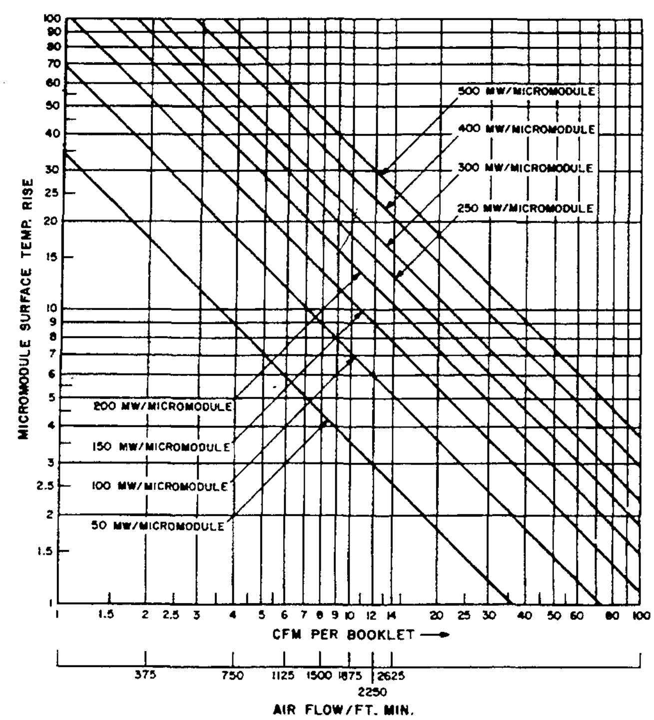


Fig. 10. Micromodule surface temperature rise *vs* cooling air flow.

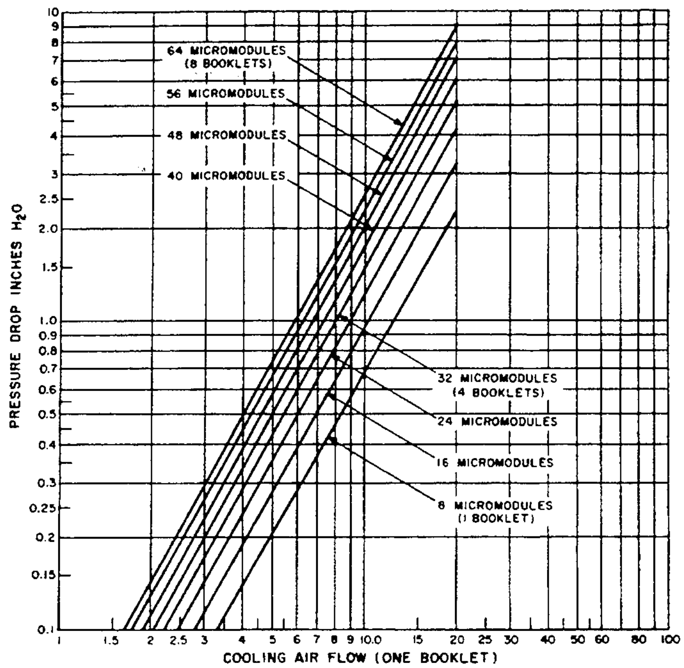


Fig. 11. Air pressure drop *vs* cooling air flow.

MICROPAC) which contains 4 micromodule booklets, or 32 micromodules, in depth. The maximum temperature rise refers to the surface temperature rise of the 32nd micromodule in the direction of cooling air flow. Thus, if a temperature rise of 15°C above maximum ambient temperature is desired by the equipment designer for micromodules with an average power dissipation of 100 mw, an air flow of approximately 4.7 ft^3/min per booklet channel is required.

Figure 11 is a graph of cooling fan pressure drop *vs* air flow per booklet channel, with the number of micromodules per channel as a parameter. Thus, to obtain an air flow of 4.7 ft^3/min per booklet channel for a circuitry section 32 micromodules deep, a pressure head of approximately 0.4 in. of water will be required. The total air flow required is the product of the required air flow per booklet channel (4.7) and the number of booklets to be cooled in parallel, i.e., the height of the circuitry section in booklets. In MICROPAC, the height is 10 booklets so that the total air flow requirement is 47 ft^3/min at a pressure drop of 0.4 in. of water.

Figure 12 is a graph of pressure drop *vs* air flow for a cooling fan of sufficiently small volume 2 in. in diameter × $1\frac{1}{2}$ in. to be efficiently employed for circuitry cooling. This graph indicates that the micromodule circuitry cooling requirements

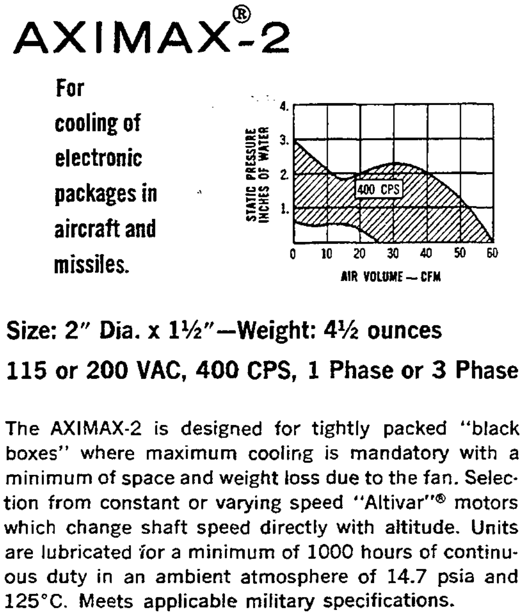


Fig. 12. Cooling fan characteristics.

(of 47 ft^3/min and 0.4 pressure drop in inches of water) can easily be satisfied by this fan. A photograph of the fan is shown in Fig. 13.

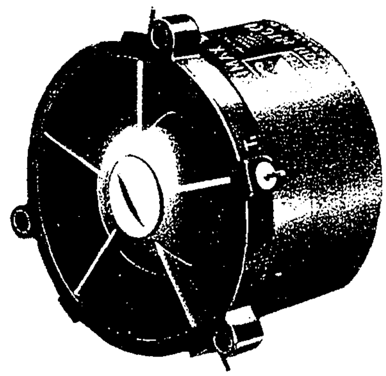
The above data indicate the feasibility of effective forced air cooling of more than 2000 digital micromodules with an average power dissipation up to 500 mw a maximum temperature rise of 65°C above ambient temperature, and use of a cooling fan of the type shown in Fig. 13. In smaller equipments with substantially fewer micromodules with power dissipates less than 50 mw per micromodule, conductive transfer of heat from the micromodule surface is feasible, as shown in Fig. 14.

CARD INTERCONNECTION AND LAYOUT

A secondary objective of the MICROPAC program was to employ, if possible, single-layer printed circuit cards. Thus efforts were directed toward the layout of double-sided printed circuit cards with plated-through holes and with a minimum of wire jumpers. The total number of different card types required for logic and memory circuitry is 56. The average number of jumpers required per board was 14; however, this can be reduced considerably, or eliminated, if pin assignments are made during printed card layout (see Fig. 15).

The MICROPAC card is fabricated from an 0.047-in. glass epoxy base material (G-11) with 2-oz copper on both sides.

The micromodules on these cards are located on an 0.025 grid to facilitate



Series	Volt	Phase	CPS	CAP MFD	Nominal RPM	Full Load Watt	Line Amps	Max. CFM	Max. S.P. At No Del.
368YS	115	1	400	0.5	20000	36	.330	58	2.80
367JS	200	3	400	—	20500	36	.140	60	3.
464YS	115	1	400	0.15	11000	10	.100	32	0.85
* 415YS	115	1	400	0.15	11000	18	.190	32	1.0
* 395JS	200	3	400	—	11000	18	.100	32	1.0

*Altivar®

Fig. 13. ROTRON cooling fan.

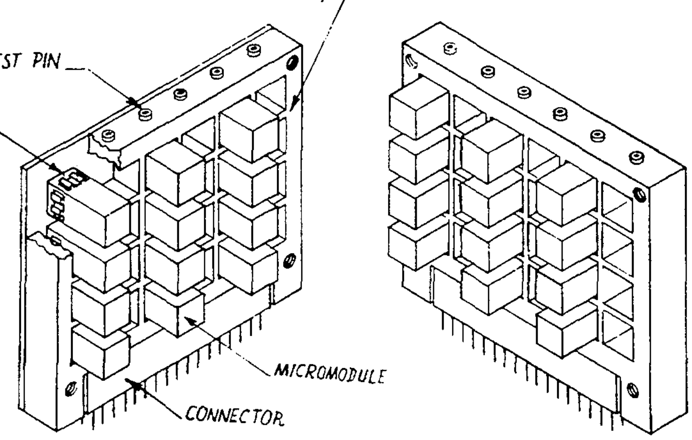


Fig. 14. Micromodule card configuration for conductive heat transfer.

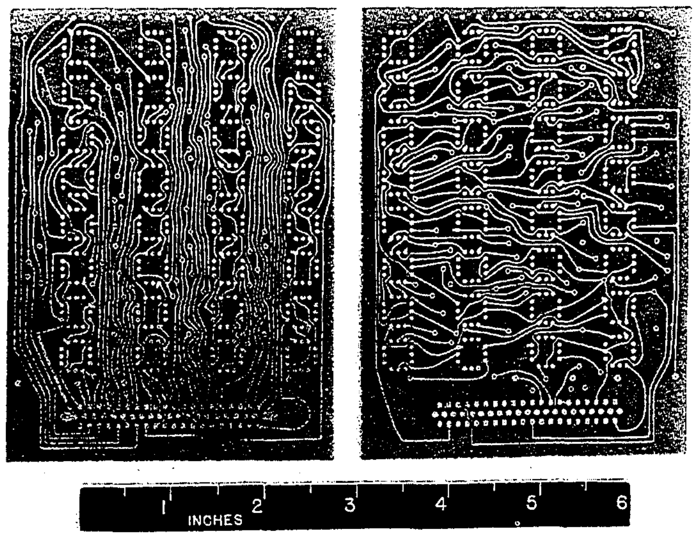


Fig. 15. MICROPAC printed circuit card layout.

standard layout and printing techniques. Plated-through holes are used for interconnections between layers and to provide additional surface area for module soldering.

In order to reduce the inductance (noise) of critical output lines without employing parallel ground conductors adjacent to these lines and an additional ground lead to each module, it was decided to attach a ground plane to the card. The ground plane is 0.005-in. epoxy with 2-oz copper which is stitched to plated-through holes of the micromodule card.

The need for jumpers on many cards, and for an auxiliary ground plane, leads to the conclusion that multilayer wiring will probably be required in future micromodule digital equipments. Multilayer cards can provide for one or more ground planes and for the effective utilization of card connectors with a larger number of pins. The increased connector pin requirement will be derived from the necessity for minimizing the number of different card types and thereby decreasing the cost of spare parts per equipment.

SUBSECTION CONFIGURATION AND LAYOUT

After selection of the booklet size and configuration, it is necessary to assemble the circuitry booklets into a circuitry subsection, preferable with a common backplane for card or booklet interconnection. The volume available for the circuitry section (10 in. high × 5.5 in. wide × 14.5 in. deep) practically dictates a subsection configuration in which the booklets are mounted in a direction parallel to the ground plane or computer width (see Fig. 16). The number of booklets in depth (4) was selected to achieve a depth dimension compatible with the memory

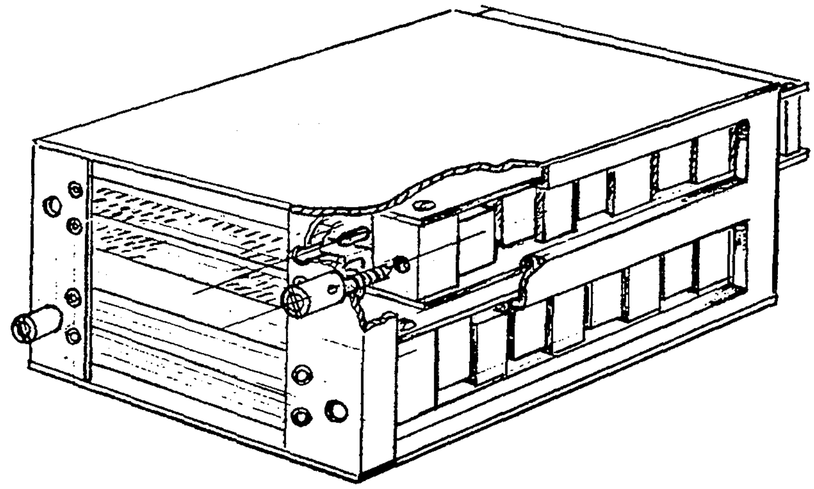


Fig. 16. Circuitry subsection configuration.

and power supply sections. The number of booklets in height (10) was selected to provide the required micromodule capacity plus adequate allowance for unforeseen contingencies. The resulting circuitry subsection provides a maximum capacity of 40 booklets or 80 cards or 2560 micromodules. A photograph of the circuitry subsection is shown in Fig. 17.

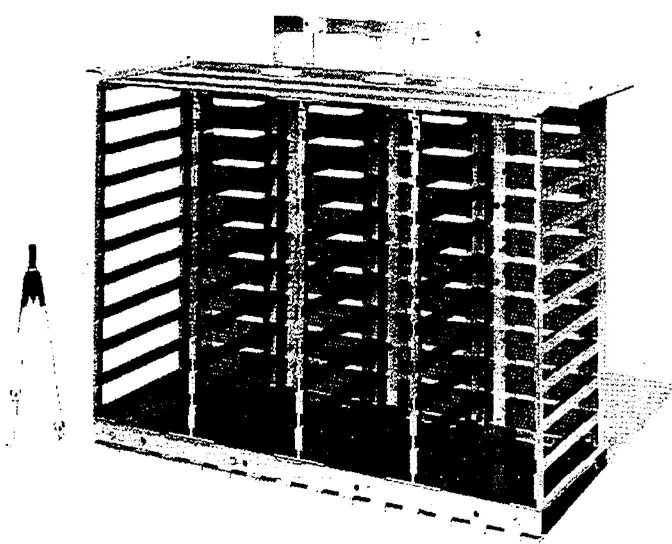


Fig. 17. MICROPAC circuitry subsection.

The circuitry subsection backplane is shown in Figs. 18 and 19 before and after completion of wiring, respectively.

Backplane wiring in large-scale high-speed digital computers has been a serious problem to equipment designers using conventional components mounted on printed circuit cards. The problem has been partially electronic and partially physical. To minimize transmission-line effect of long interconnecting leads carrying pulse signals with short resistance, it has been frequently necessary to use properly terminated coaxial cable or twisted pair wires. Such usage contributes to a backplane access problem already made difficult by the logical complexity of the computer.

In this case the backplane wiring was carefully planned and both electrical and mechanical difficulties anticipated. After an extensive analysis approximately 600 leads were routed and cabled, 2100 were point to point, 130 were twisted pairs, and 80 were shielded twisted pairs. This analysis has reduced our backplane wiring build-up and thereby minimized wiring time and test and debugging cycle.

As shown in the mock-up, the circuitry section is hinged to provide simultaneous access to the test points on the printed circuit cards and the backplane wiring. Electrical connection to the hinged section was implemented by interconnecting ribbon cables with 12–16 and 48 conductors to facilitate the 180° hinging section.

This connector and backplane design is compatible with the latest techniques employing multilayered wiring, and will be incorporated in production quantities of this or similar type computers.

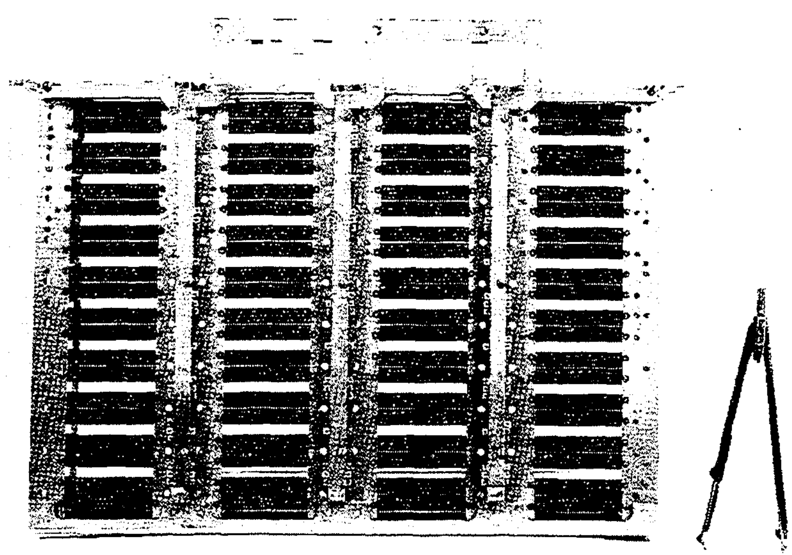


Fig. 18. MICROPAC circuitry backplane (before wiring).

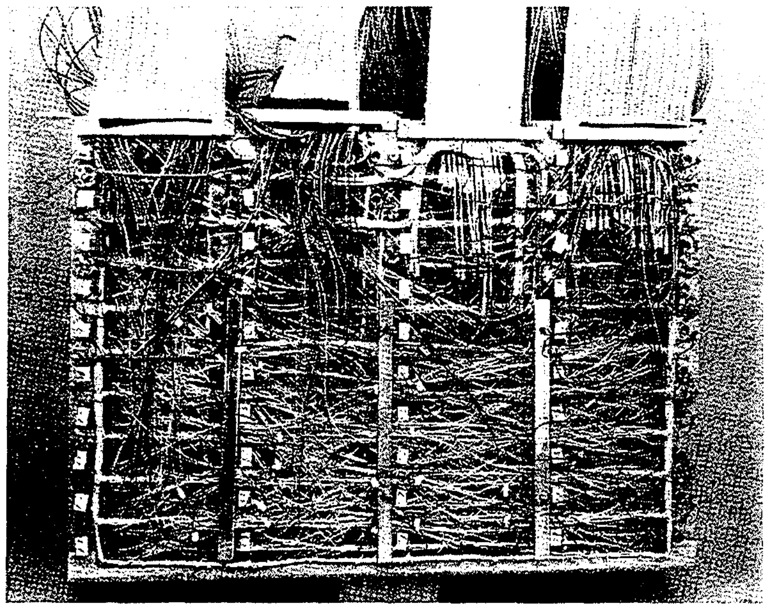


Fig. 19. MICROPAC circuitry backplane (after wiring).

The booklet frame is a precision machine, welded, and riveted assembly maintaining close tolerances for booklet insertion and extraction. A single extractor screw and spacer block are employed as indicated in Fig. 16 to overcome the initial 40–60-lb extraction force of the 122 pins of the booklet connectors.

As a result of the high ratio of connector pins per square feet of backplane area (5000 pins/ft^2 or 26 pins/linear inch) some modifications of existing wiring techniques were employed. As a result of a backplane experimental investigation, a modified wire-wrap technique was selected and employed. This approach (using #28 solid wire with 3-mil Teflon insulation) facilitated the mechanical attachment of the interconnecting wire to the 0.028-in.-diameter connector pin. One and one-half or two wraps of wire are made around the connector pin, which was then soldered at various levels of wire build up. It is proposed, with a slight modification of the connector terminal, that the computer could be debugged and tested and then soldered prior to environmental testing or delivery to the customer.

Despite the apparent complexity and wire density (over 6000 connections), wiring time using these techniques was less than equivalent conventional rack-mounted equipment.

MICROPAC OVERALL ASSEMBLY

In the preceding discussion, the design considerations leading to the circuitry subsection configuration were described. It is now necessary to indicate the mechanical design concepts which were employed to provide a single unitized assembly capable of rack and panel mounting or vehicular mounting within a transit case. This unit must provide space for the circuitry, memory, power supply, and control panel subsections plus space for miscellaneous items such as connectors, fans, filters, etc. The MICROPAC unit which has been designed to meet this requirement is shown in Fig. 20. The overall layout and distribution of major subsections within the single transit case is shown in Fig. 21. The physical characteristics of the MICROPAC computer shown in Figs. 20 and 21 are as follows: volume—2.70 cu-ft; weight—90 lb; outside dimensions—17.8 in. wide × 12.6 in. high × 21 in. in diameter; inside dimensions (usable)—16.0 in. wide × 11.3 in. high × 20.3 in. in diameter. The complete equipment is designed to operate within the range of environmental conditions described in the introduction: to withstand up to 100 *g* shock loading, and the temperature and vibration excursions tabulated listed in Table I.

The shock and vibration requirements dictated a choice between two divergent design paths, namely, either no shock or vibration isolation or extensive shock isolation. It was decided to adopt the former approach for the following reasons: (1) the size of the unit, allowing clearances of a sufficient nature, would increase the size of the computer beyond that specified; (2) it is most probable that the shock isolators would bottom out at some condition of the test, and when this happens the resultant secondary shock may attain twice the magnitude of the initial impulse; and (3) without shock mounts it is possible to integrate the strength of the case with that of the internal members to form a unit of the desired strength.

The case is a unit constructed of sheet aluminum with extruded aluminum end areas for both structural stiffening and water scaling according to specifications. The Zero Manufacturing Company of Palmer, Massachusetts, is the vendor for this unit.

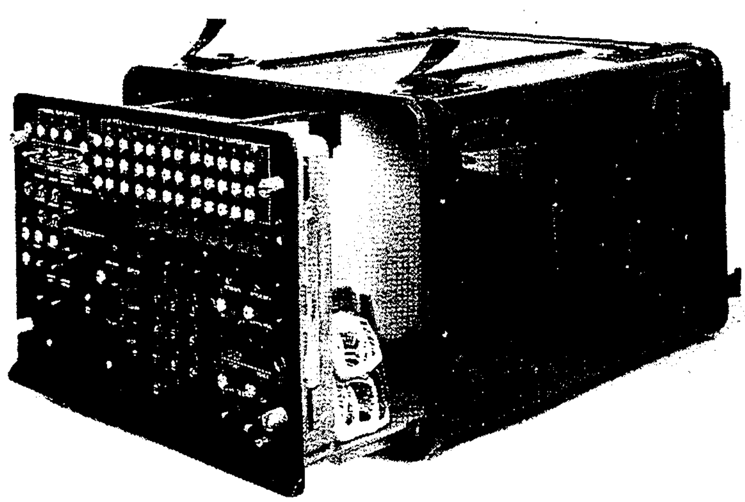


Fig. 20. MICROPAC with chassis rolled out.

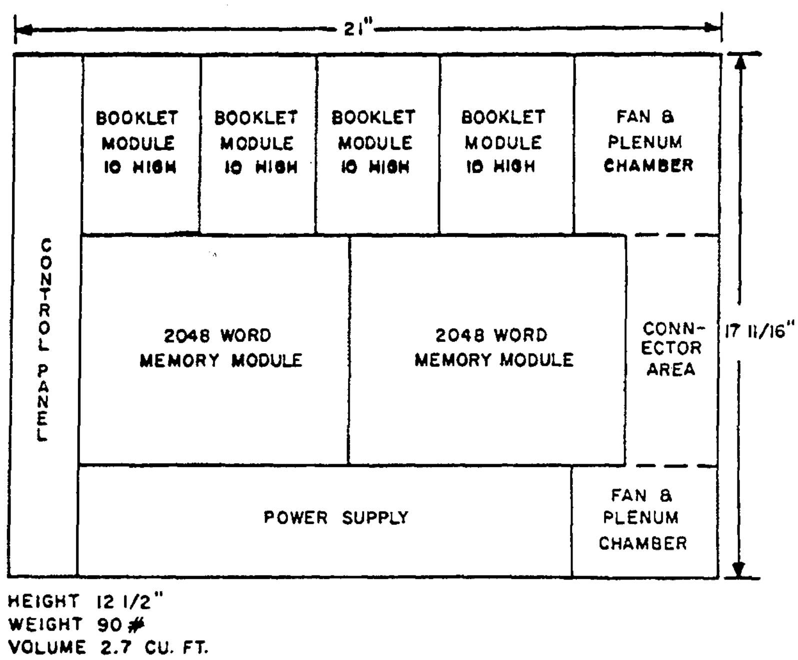


Fig. 21. MICROPAC layout.

The welded aluminum channel was chosen as the basic building element of the structural section of the computer (see Fig. 22). The basic structure is a welded box section at each end of the computer, tied together by a chassis, and the structure which houses the memory stacks. The structure which houses the memory stack is constructed of glass epoxy laminate. This material was chosen to combat the problem of thermal isolation. The conditions of design are that the memory stack must be maintained at a temperature of $+40°$ to $+60°$C.

To allow for this condition and also maintain the maximum strength, glass epoxy has a tensile strength equal to or greater than the aluminum and a greater thermal resistance than the aluminum. These factors allow the optimization of the heaters and coolers that are required for the memory stack. To aid the glass epoxy case in the thermal problem, insulation material was added. This material, Polyurethane foam has a density of 2 to 4 lb/ft^3. This material is being used inside and outside the memory housing. This housing will accommodate the two memory stacks (modules) as required.

The requirements of the logic circuitry section (booklets) for test-point accessibility was the major factor which determined the slide design. The slides had to be able to carry the moving weight and support it in the fully extended position. The moving weight is estimated to be 75–80 lb. This requirement and the space problem of the test-point accessibility required a slide of very shallow dimensions. None was available when used in the normal position. The solution was to rotate the slides 90°. To use a slide in this condition requires that the slide be derated to

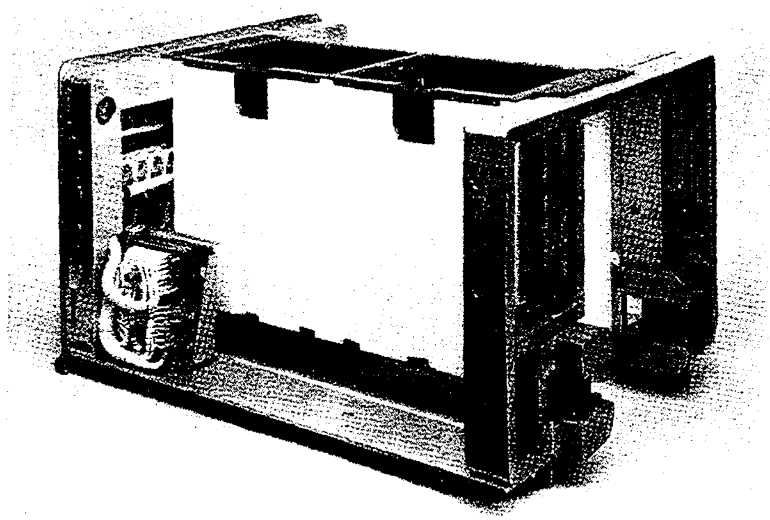


Fig. 22. MICROPAC main chassis.

50% of its normal value. Grant Pulley and Slide Company was able to supply a unit to fill these needs. This slide will lock in the open position only. In the closed position, load pins at the rear of the unit will lift the load off the slide. This will prevent damage to the slides and to the unit under the test conditions. Part of the load will be carried by a set of steel pins at the rear of the unit. The major portion will be carried by the case and forward box section. In the normal operating condition, the unit loads are carried by a combination of the case and chassis. Under this condition, all the metal is carrying its share of the load.

The memory, power supply, and control panel sections are plug-in units. It was not feasible to design the circuitry section as a plug-in unit because of the large number of interconnections required (over 700) with the other sections. A more detailed description of the design of the memory, power supply, and control sections of MICROPAC is contained in an RCA document, entitled "*MICROPAC Development Program—A Status Report.*"

SPECIAL TOOLS

During the MICROPAC development program, it became necessary to design and develop the following special tools to reduce the cost of assembly and to implement the micromodule packaging techniques.

The Soldering Iron. Figure 23 is a photograph of a soldering iron which provides a rapid, simple, efficient, and safe means for micromodule removal. The twelve tips provide quick controlled heat to the corresponding twelve pins of the

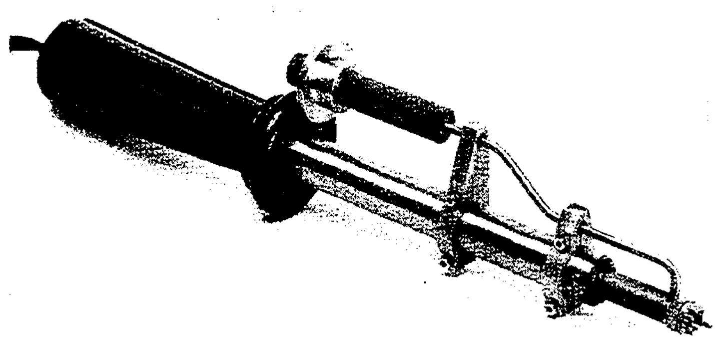


Fig. 23. Micromodule soldering iron.

micromodule, and as the solder approaches flow point the spring-loaded center pin ejects the micromodule.

Manual Wire Wrap Tool. As discussed in previous section, a modified wrap technique was employed. A special tool shown in Fig. 24 was designed. The wire is stripped to a predetermined length and then inserted in the off-center hole and bent at right angles to the tool stem. The tool, via the center hole, is

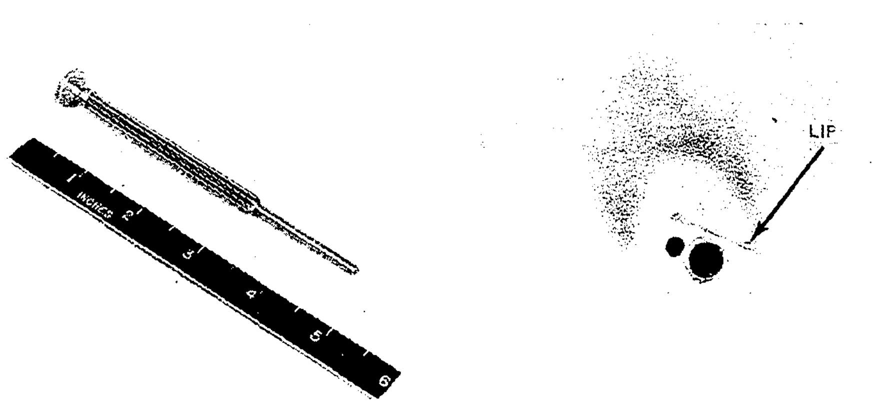


Fig. 24. Manual wire-wrap tool.

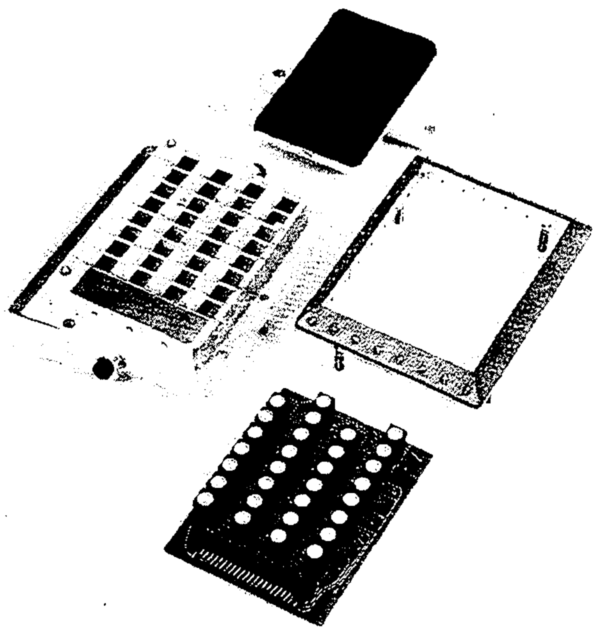


Fig. 25. Micromodule alignment and dip-soldering fixture.

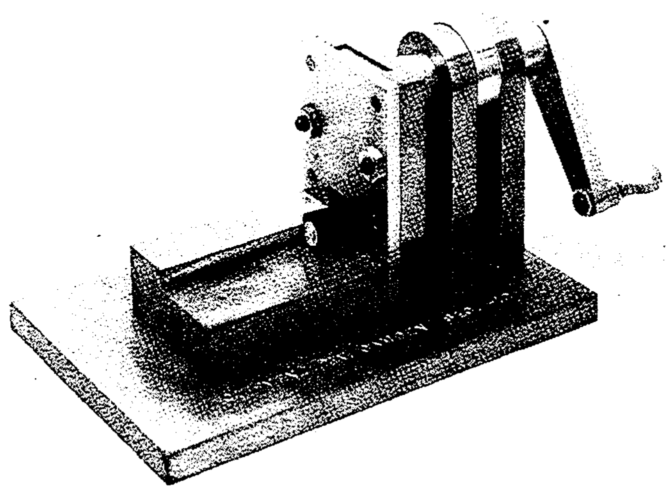


Fig. 26. Micromodule lead cutter and straightener.

slipped over the connector pin and turned, resulting in a modified wire-wrap termination to be soldered at a convenient time.

Module Alignment and Dip-Soldering Fixture. An investigation of the thermal considerations of micromodule heat transfer determined that the spacing and perpendicularity of the micromodule was a prime consideration to effectively cool a row of modules 8 wide by 32 deep. The egg crate shown in Fig. 25 was designed to align the module on the printed card and also serve as a fixture for dip-soldering the card assembly.

Micromodule Lead Cutter and Straightener. Figure 26 is a photograph of a micromodule lead cutter and straightener which can be adjusted to shear the micromodule pins to the desired length. This is accomplished with minimum burring for ease of module insertion into the printed card.

CONCLUSIONS AND FORECAST

At the time of presentation of this paper (August 1962), MICROPAC will be undergoing final systems and acceptance tests. The preliminary tests which have been conducted to date (June 1962) of micromodules, micromodule logic and memory plug-in cards, and of major sections of the computer indicate that the feasibility of micromodule circuitry packaging in militarized digital equipment has been demonstrated. Furthermore, equipment design techniques (logic, circuitry, packaging, etc.) have been developed to permit the efficient and effective application of micromodular circuitry packaging to other digital equipments. Such techniques are now being applied toward the design and fabrication of a large-scale, high-speed general-purpose militarized digital computer referred to as MICROPAC (*Micromodule Random Access Computer*). This computer will contain a maximum of 35,000 logic and memory micromodules, four 16,384-word high-speed memory units, and a dc power supply within one MIL-STD-189 rack, 5 ft in height.

The MICROPAC program has not only provided micromodular equipment design techniques for militarized digital equipment but has also crystallized and/or clarified the distinction between micromodule circuitry packaging and the various forms of integrated electronic or solid circuitry techniques which have been advancing rapidly during the past few years. The micromodule is truly a method for efficiently packaging and interconnection of units or elements of electronic equipment. In 1958, when the micromodule program was started, these units or elements were individual electronic components such as semiconductors, resistors, capacitors, etc. Today, it is quite feasible to consider high-population digital circuits (logic gate, flip-flop, etc.) as integrated units or elements of digital equipment. To efficiently accommodate six to eight such integrated circuit elements, the advanced micromodule is currently being designed by RCA. This micromodule is the same as the well-known, currently available micromodule except that it provides for 28 (instead of 12) external connections. The advanced micromodule concept is illustrated in Fig. 27.

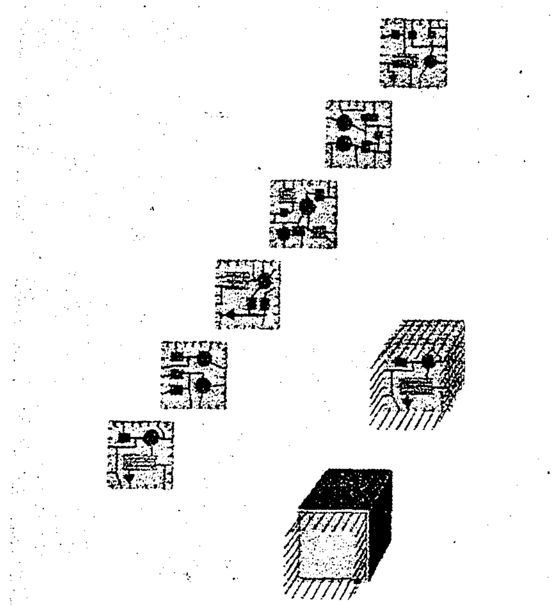


Fig. 27. Advanced micromodule concept.

Thus, the militarized digital equipment of the sixties can make effective and economical use of both integrated semiconductor circuits (in high-population repetitive circuits) and individual components (in low-population, special circuits) by the employment within the same piece of digital equipment of both the 28-pin and 12-pin micromodules. The equipment packaging techniques developed under the MICROPAC program are applicable to both types of micromodules and are available to all equipment designers and users.

DISCUSSION

Q. (Harvey Zaid, Nortronics, Anaheim, Calif.) On your advanced micromodule, you indicated that you are using the same form factor, which I assume will be the 0.36 square, and, yet, according to the last slide it looked as though you had about 32 pins. How do you anticipate interconnecting these modules?

A. It actually has 28. Every wafer doesn't need, or have, 28 connections. Connections alternate between wafers so that not more than 4 riser wires are connected to each wafer.

Q. (John Rykaczewski, Martin/Orlando, Fla.) I wish you would briefly discuss the cooling plenum chamber; also is this an open exhaust type of blower, or some other type?

A. As the paper indicates, we are using a Rotron Axiomax 2. It develops about 4 in. of water and in our particular application it supplies about 40 cfm. As you further investigate the paper, (it would be quite lengthy to go into the complete discussion) we have calculated that each row of booklets requires roughly 2.75 cfm of air at about ½ in. of water. I have a copy of the data taken to determine the pressure and the volume of air required. If anyone is interested we would be happy to pass it on to you.

Q. (Joe Ritter, Electronic Modules Corp., Timonium, Md.) I have two questions. First, do you have any figures on the heat rise from one of these micromodules dissipating 113 mw without forced air cooling?

A. This would depend entirely on the ambient temperature.

Q. Well, talking about a heat rise from room ambient, do you have any figure at all?

A. I would say the temperature rise at 70°F might be as high as 25°C.

Q. The other question is related to cost. You talk about cost in your paper, but it has not been discussed at all here, and you give a lot of comparative values. Can you give us some idea of what you think the cost is now and how you arrived at these comparative figures for the future?

A. Based upon fixed-price quotations received by our activity, micromodule cost in quantity (delivered in 1963) is less than the equivalent circuit in a conventional package. An approximate price for *militarized* silicon diode-transistor logic circuitry with a pair delay of 60 nsec, produced in quantity in 1963, is less than $20 for a two-circuit module, or less than $10 per circuit.

Q. (Leonard Schehr, Martin-Marietta, Baltimore, Md.) Is your backplane point-to-point wiring soldered or is this a mechanical crimp-type connection?

A. In order to facilitate the wiring (the connector pins are on 1/10-in. centers, three rows to a connector) we used what we call a modified wire wrap technique. There is a photograph of the tool in the last pages of the paper. We insert the solid wire (3-mil teflon inculation) into the hole and then slip the tool over the connector pin and wrapped approximately 2½ turns. As the wire build-up continued, the wireman goes back and applies solder to each of the connector pins.
(Mr. Coleman) I would like to add one point. The backplanes for card interconnection are designed for printed wiring. We have received quotes from several companies indicating that the 2800 to 3000 wires per backplane could be accommodated in a multilayer circuit board with about 12 layers. It is our intention to employ a multilayer printed-wire backplane once the logic and wiring errors have been eliminated.

Q. (J. J. Bond, Fab-Tool, Inc., Englewood, Colo.) Do you consider soldering an adequate method of interconnection between your Micropac modules or does this require welding?

A. The shock and vibration tests that we have conducted to date indicate that the dip-soldering technique that we use for the printed card is satisfactory for our application. We use a two-sided card with plated-through holes, which we believe assists in the soldering application.

Q. (Bob Lomerson, Westinghouse, Newberry Park, Calif.) You indicated that you have a 28-pin module coming up—this would mean 7 pins per side.

A. That is correct—7 pins per side.

Q. This would give you about 40/1000 between pin centers.

A. That is correct; actually it is 37.5/1000.

Q. That gets pretty tight when you put it in a board. What size wire diameter are you going to use?

A. The diameter of the wire is 10 mils.

Q. Are you going to put this into a circuit board?

A. Well, we are proposing several schemes for doing this. One is a lay-up welded type scheme wherein we weld between pins on a base matrix and then interleaf mylar and then another layer of welded matrix. Another possibility is multilayered wiring techniques. There are people today who are approaching our requirements and they have contacted us with very fine line definition in printed wiring.

Q. Can they get this for soldered configurations on a multilayer board with this type pin?

A. Yes.

Q. (Martin Camen, Bendix Corp., Teterboro, N. J.) How did you derive this form factor of 0.36 × 0.36? I believe there is a new Navy Mil Spec out on thin-film modules and this seems to be quite out of line with it. How is this going to affect your program?

A. I am afraid that the Army and the Navy will have to adjust this difference themselves.

Q. Well, if a contract was put up for bid and this was one of the requirements, would you retool, or would you just not bid on the contract?

A. I believe that we would deal with this problem if and when it arose.

Q. Because this form factor seems to be unique with RCA, I doubt very much if most of the people are using it.

A. The form factor is actually *not* unique with RCA. The U.S. Army has provided for at least two alternate sources of supply (Paktron and P. R. Mallory) for micromodules. Other companies (at least three known to us) are actively engaged in their own micromodule program. The Army has made public statements indicating their intention to employ micromodule packaging in a variety of militarized electronic equipments.

Q. (Everett Higdon, Martin-Marietta, Denver, Colo.) On the back of your plugs where you wire-wrap them, and then solder—doesn't this take up quite a bit of manufacturing time?

A. We have made some unofficial time studies. Obviously, as Mr. Coleman indicated, we have only built this one machine; i.e., Micropac. In addition to this machine, we are also building equipment in standard relay racks that has already been discussed today; on a wire-to-wire basis, we find that we get 20% more efficiency; i.e., 20% more wires are applied per day on this small Micropac backplane compared with two or three men working between one or two relay racks.

Q. (Jack Dunne, Cinch Mfg. Co., L.A., Calif.) I am wondering, for maintenance in the field, if you are planning for replacement of the modules on the printed circuit boards with some sort of a plug-in feature or socket that could be standardized with your particular type of product?

A. We are planning for replacement of plug-in cards (containing from 10 to 30 micromodules) at the first echelon. At higher echelons, a card tester would be used to locate the defective micromodule, which would then be replaced.

The micromodule reliability data we have obtained thus far indicate failure rates approaching equivalent modules composed of Minuteman high-reliability components. As a result, one of the most significant sources of equipment *unreliability* is contact connections. Thus, in digital equipment design, we are strongly motivated to avoid contact connections of the type which would be employed for plug-in micromodules.

Selection of Packaging Materials for Oceanographic Instruments

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This paper presents a general discussion of topics which contribute to an understanding of the problems involved in materials selection for long-life oceanographic instruments. Included are discussions of marine environment, fundamentals of corrosion, fundamentals of fouling and attack, and the behavior of common engineering materials in sea water.

INTRODUCTION

GOVERNMENT INTEREST in basic underwater research, for reasons of defense, has exposed the need for a new generation of oceanographic instruments. Programs such as the Navy's projected ten-year, billion dollar program of ocean study, TENOC-61, have as their objective basic underwater research on a global scale[1]. The oceans and seas cover 70.8% of the earth's surface, an area far too large to study in a single decade with the archaic instruments in service today.

Included in the stringent requirements imposed on this new generation of instruments is long life, involving in some cases from one to six years of uninterrupted service. This is primarily a problem of materials selection and the related effects of corrosion, fouling, and attack. This paper presents a general discussion of topics which contribute to an understanding of this problem of materials selection for long-life oceanographic instruments. Included are discussions of the marine environment, fundamentals of corrosion, fundamentals of fouling and attack and the behavior of common engineering materials in sea water. Each of these topics is extremely complex, and has been subject to much formal investigation. In generalizing about them there is the danger of becoming misleading. The information presented is intended as an introductory guide to the subject of material selection. For detailed advice the reader is referred to consulting specialists in each particular field.

THE MARINE ENVIRONMENT

The marine environment is by far the most complex on earth. Its billions of tons of water in continual motion constitute a heterogeneous mixture of powerful physical, chemical, and biological forces. To date man has learned very little of this "inner space." From what is known of the environment, however, some aspects of material behavior can be predicted.

The major cause of corrosion is the fact that sea water is such a good electrolyte. However, corrosion itself is not the sole factor limiting the useful life of an instrument. *Fouling*, a term describing the assemblage of animals and plants which clings and grows on almost any submerged object, causes many undesirable effects. For example, temperature sensors lose their response time when fouled; rotating current flow meters become unbalanced or completely cease operation; lenses on optical devices become overgrown; anchor cables exert much higher current drag forces due to their increase in size; and floats lose buoyancy due to the weight of the fouling. Certain marine organisms also attack materials and stimulate corrosion. Barnacles cut their way through most organic finishes to expose bare metal. Some organisms bore into the nonmetallic materials for protection, while others attack the material as food.

Those parameters of the marine environment significantly affecting corrosion, fouling, and attack include temperature, oxygen content, light, current velocity, conductivity, and pressure.

Temperature

With increasing water temperature, corrosion, fouling, and attack are of greater concern, primarily because of increased fouling activity but also because of increased conductivity. As a general rule, temperatures above 15°C are conducive to fouling[2]. Figure 1 illustrates the practical extremes of water temperatures in the oceans plotted against depth.

Oxygen Content

Oxygen in sea water plays an important role in corrosion. Its presence can inhibit or greatly accelerate corrosion, depending on the material and the situation. In low-oxygen areas sulfate-reducing bacteria are a problem because in reducing

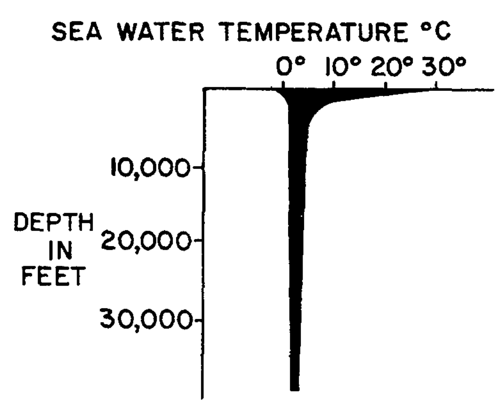

Fig. 1. Extremes of water temperature in the oceans of the world *vs* depth[3–7].

the sulfates they liberate hydrogen sulfide, which in concentration can be corrosive to certain materials.

The oxygen content of the oceans is dependent primarily on surface conditions. It is believed that oxygen found at 20,000 ft, for example, comes from the surface, borne by undersea currents.

Wind and waves aerate the surface waters aided by the photosynthetic activity of plants. In general, the oceans are aerobic (containing oxygen) throughout, with only the last few feet from the bottom becoming anaerobic. Figure 2 illustrates a general midocean oxygen-depth profile.

Light

Light, a prime requisite for plant life, becomes gradually extinct at a depth of approximately 600 ft. At 100 ft the light is sufficiently reduced to inhibit plant activity.

Conductivity

The conductivity of sea water increases with salinity and temperature. In the major oceans the salinity shows little variation, but over the temperature range 0–25°C the conductivity of sea water almost doubles[8], contributing to the fact that materials corrode more severely in warmer waters.

Current Velocity

Current velocity varies considerably with location, weather, time, and depth, and must be considered in materials selection since it directly affects the rate of corrosion/erosion of many substances. In most cases, the corrosion products formed on a metal surface tend to inhibit further corrosion. If they are soft, however, the current will wash them away thereby increasing the corrosion rate.

Figure 3 illustrates the range of current velocities found in the oceans. The highest velocities are found in wind-driven currents at the surface.

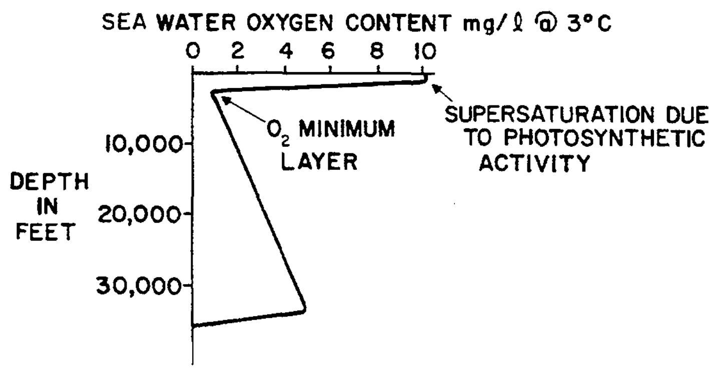

Fig. 2. General midocean profile of oxygen content *vs* depth[3,18].

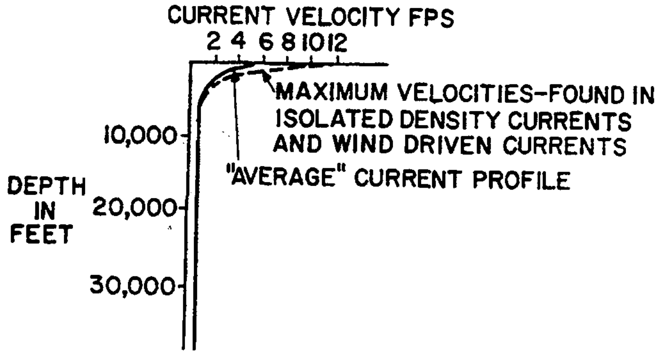

Fig. 3. General profile of ocean current velocities *vs* depth[3,9].

Pressure

The effects of high pressure on corrosion and material behavior have not been determined. It is known that fouling can occur in the deeps but the organisms are of a different variety than those found near the surface, and their growth and activity are considerably slower.

The pressure increases almost linearly with depth. Variations of approximately 1% occur due to density changes[8]. For general calculations, it is sufficient to use 64.4 lb/ft^3 as the average density of sea water. For convenience a pressure–depth plot is included in Fig. 4.

CORROSION FUNDAMENTALS

The driving force behind the corrosion of metals in sea water is electrochemical. The corrosion process can be most simply described by likening it to the electrochemical common wet cell, having an anode and cathode connected by an external circuit and immersed in an electrolyte (see Fig. 5). An electric current is generated and the anode is driven into solution. The tendency for the reaction to begin is a function of four variables: the corrosion potential of the anode, the

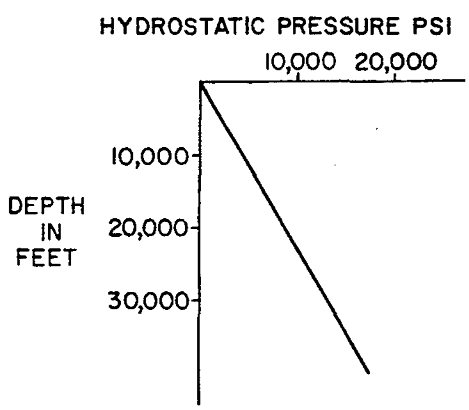

Fig. 4. Pressure *vs* depth based on an average sea-water density of 64.4 lb/ft^3.

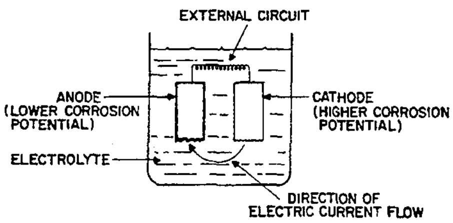

Fig. 5. Corrosion cell. The process of corrosion can be likened to a common wet-cell battery. A current is generated and the anode is driven into solution. Factors influencing the cell's activity are: (1) corrosion potential of the anode; (2) corrosion potential of the cathode; (3) resistance of the external circuit; and (4) conductivity of the electrolyte.

corrosion potential of cathode, the conductivity of the electrolyte, and the resistance of the external circuit.

The corrosion potential of a freely corroding metal in a particular solution is measured at any instant by the potential between the metal surface and its ions in the solution. It is, in essence, a measure of the tendency for the metal to go into solution. Table I shows a list of metals, arranged in order of increasing corrosion potential in sea water, with those metals having lower potentials being anodic to those having higher potentials[9–12]. It is referred to as the sea-water galvanic series and differs slightly from the electromotive-force series in that it is not theoretical but is based on actual tests with materials in sea water. The order of arrangement differs in other electrolytes. Also, being experimental, differences in the relative positions of metals in the sea-water galvanic series have been published by various sources. For example, the author found titanium reported in the positions marked with an asterisk.

In general, with reference to the galvanic series, the metal having the lower corrosion potential (anodic) will be driven into solution when connected to another metal in a corrosion cell. This is described as galvanic corrosion. However, there are exceptions and care must be taken when designing with materials close together on the galvanic scale. Figure 6 indicates some of the more common reversals.* The areas in black indicate that medium to severe corrosion will occur when a small exposed anodic area is coupled to the large exposed cathodic area.

On any metal surface, various nonhomogeneities are responsible for variations in corrosion potentials. Anodic and cathodic areas result from differences of composition, discontinuities in protective films and coatings, inequalities in stress, and differences in surface texture. In the presence of an electrolyte, these surface corrosion cells are activated (see Fig. 7), thus driving the anodes into solution and forming surface pits. Most metals resist pitting and corrosion through the formation of uniform protective films and coatings—products of the corrosion reaction. However, a few materials, such as steel and iron, are not protected by their corrosion products.

* The reader is referred to the *Corrosion Handbook*, H. H. Uhlig [9] for a complete tabulation of similar data.

TABLE I

Galvanic Series of Metals in Sea Water

(HIGHEST CORROSION POTENTIAL—ANODIC)
Magnesium
Zinc
Galvanized Steel
5052 Aluminum
1100 Aluminum
6061 Aluminum
Alclad 3003
Cadmium
2024 Aluminum
Mild Steel
Cast Iron
304 Stainless Steel (active)
316 Stainless Steel (active)
Lead
Nickel (active)
Inconel (active)
Hasteloy C (active)
Brasses
Copper
Bronzes
Copper–Nickel Alloys
*Monel
Silver Solder
Nickel (Passive)
Inconel (Passive)
Titanium (Passive)
304 Stainless Steel (Passive)
316 Stainless Steel (Passive)
*Hasteloy C (Passive)
Silver
Gold
Platinum
(LOWEST CORROSION POTENTIAL—CATHODIC)

* Titanium reported in some sources.

In most instances, corrosion is proportional to the amount of dissolved oxygen reaching the metal surface. Protective coatings and films may exclude the oxygen, but not the electrolyte, from the surface. The resulting oxygen concentration cells are the source of many corrosion problems. An aerated electrode is cathodic to a similar but oxygen-free electrode, and in an electrolyte a current will flow. Three oxygen concentration cells are illustrated in Fig. 8. In the first, a metal rod driven into the low-oxygen ocean bottom has its top exposed to aerated water. Accelerated corrosion will occur on the oxygen-free surface near the interface. The second illustration describes an oxygen concentration cell formed by a barnacle with corrosion occurring in the oxygen-free zone under the barnacle. The third illustration describes one form of crevice corrosion in which the exclusion of oxygen in crevices forms oxygen concentration cells.

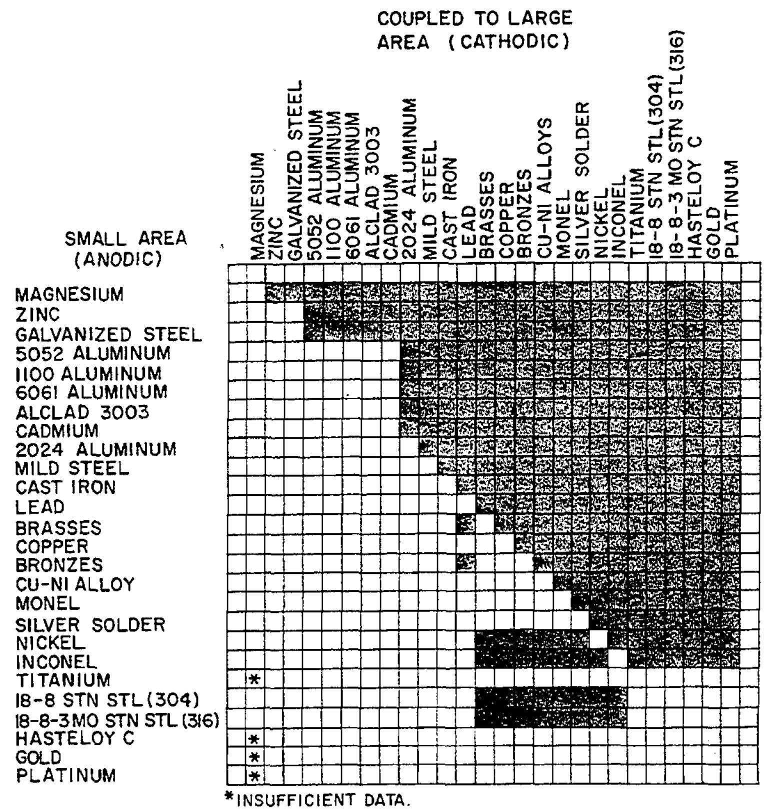

Fig. 6. Sea-water corrosion of galvanic couples. (Materials arranged according to sea-water galvanic series[9].) The areas in black indicate that medium to severe galvanic corrosion can be expected in sea water when a small anodic area is coupled to a large cathodic area.

The terms *active* and *passive* are used to describe the corrosive state of such metals as stainless steel, titanium, and nickel, which in the passive state are protected by a thin protective film. With reference to the galvanic series it can be seen that stainless steel, for example, in the active state is strongly anodic to the passive state. In a crevice, where sea water penetrates, where oxygen is excluded, and where the protective oxide film is destroyed, severe corrosion can take place.

Pitting, galvanic corrosion, and crevice corrosion are the sources of most material problems in oceanographic instrument design. Many other mechanisms of corrosion such as freting corrosion, intergranular corrosion, and stress corrosion must be considered, but they apply to a much smaller number of design problems.

THE PREVENTION OF CORROSION

Pitting

The tendency for a surface to pit is related to nonhomogeneities on the surface. By applying a coating, such as paint, which excludes the electrolyte, corrosion is

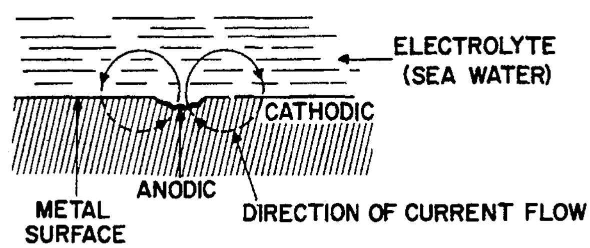

Fig. 7. Metal surface corrosion cell. (Nonhomogeneities in the surface result in anodic areas. In sea water, a current is generated and the anode is driven into solution forming a pit.)

prevented. Polishing also renders a surface more uniform and considerably reduces the tendency to pit.

Galvanic Corrosion

The rate at which one metal corrodes, when in electrical contact with a more noble metal in a common electrolyte, is primarily a function of the difference in corrosion potentials and the relative areas. For example, a small aluminum buoy anchored with a long stainless steel cable will corrode rapidly and be very short-lived, while a large aluminum assembly put together with stainless steel hardware will show little added corrosion when submerged in sea water. Galvanic couples are easily formed in welding and care must be taken to know the nature of the welding material.

Galvanic corrosion can be prevented by a coating which excludes the electrolyte. A ruptured coating, however, can cause severe corrosion and it is best to choose materials very close together in the galvanic series, electrically insulate the materials from each other, and carefully observe the rule of relative areas.

Galvanic protection of materials is an effective method for minimizing corrosion. For this application a sacrificial anode is deliberately chosen. Galvanized steel and alclad aluminum are examples of galvanically protected materials.

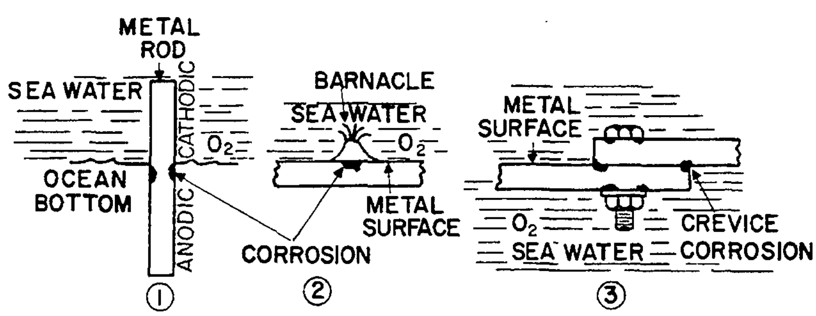

Fig. 8. Oxygen concentration cell corrosion. (An aerated electrode being cathodic to a similar but oxygen-free electrode, is the cause of severe corrosion—especially with those materials relying on a passive oxide film for protection such as stainless steel. Illustrated are three instances in which differences in oxygen concentrations result.)

Crevice Corrosion

Crevice corrosion generally describes the corrosive attack which takes place, for a number of reasons, at the junction of two surfaces having crevices or pockets. Differences in oxygen levels or metal-ion levels result in a concentration cell. (See Fig. 8.) Those materials relying on a passive film are most susceptible to crevice corrosion, since in a crevice the protective film is usually broken down, the area becomes active, and galvanic corrosion follows.

Crevice corrosion is usually accelerated in joints formed by metallic and nonmetallic materials. Nylon and stainless steel form very corrosive joints, for example.

Braided cables, screw threads, and linkages have inherent crevices and care must be taken to select materials less prone to crevice corrosion. Where possible, protective coatings should be used to prevent the electrolyte from entering the crevice.

THE CORROSION RESISTANCE OF MATERIALS IN SEA WATER

Over 20 years ago systematic long-term studies were initiated to gather basic data on the corrosion resistance of materials upon exposure to sea water. The large-scale exposure programs of the U.S. Naval Research Laboratory in the Panama Canal Zone and of the International Nickel Company at Harbor Island, N.C., were probably the most extensive. Since then over 30 universities, nonprofit organizations, and private industrial firms have been involved in similar programs. The results of these programs have provided extensive data on the corrosion behavior of a large number of materials exposed at or near the ocean surface or in laboratories using synthetic sea water.

Little is known of material behavior in the deep sea, and strong arguments are presented against the extrapolation of surface data to the deep-sea environment. The difference in marine biology and chemistry, as well as the different pressures, temperatures, and oxygen conditions at great depths may very well alter the corrosion behavior of materials in an unpredictable manner.

For these reasons, a few organizations have recently begun deep-water materials studies of very limited scope. Included are the U.S. Naval Research Laboratory, which has placed samples in the Atlantic Ocean near the Bahama Islands at a depth of approximately 5500 ft[13], and the General Electric Company, in cooperation with the Woods Hole Oceanographic Institute, which has placed materials at depths ranging from 5 to 15,000 ft in several locations between Boston and Bermuda. Unfortunately, data from these and similar experiments will not be forthcoming for several years. Some practical data are currently available from the work done on submarine cables by the American Telephone and Telegraph Company but these data deal primarily with the unique environment of the ocean floor at depths not exceeding 15,000 ft. Because material behavior in the deep ocean is still a matter of speculation the packaging engineer is forced to rely on and extrapolate surface data.

A survey of operational oceanographic instruments reveals that stainless steel and brass have been favored as construction materials. Where these materials have been maintained properly, corrosion has not been a problem. This can be explained by the fact that the instruments are immersed only for short durations, and only in rare cases up to as much as five days. While the instruments are very susceptible to corrosion and fouling, their short submersion periods have not been long enough for these effects to be of significance. Only in isolated cases, where strong galvanic couples have been formed, has corrosion been a problem.

The instruction manual for oceanographic observations[14] outlines the routine care each instrument must receive after every daily submersion. All instruments must be cleaned, rinsed in fresh water, oiled, and in some cases parts of the instrument stored in light oil. Oceanographic instruments capable of maintenance-free operation for extended periods in the extremes of the environment must rely on the resistance of their materials, however.

The evaluation of corrosion-resistant materials shown in Fig. 9 is based on the author's judgment. Although in general the more noble materials offer the best long-term corrosion resistance to sea water, there are exceptions as illustrated in Fig. 9. The variable resistance to corrosion of some materials, such as stainless steel, is a matter of application. Stainless steel which is free of crevices and in

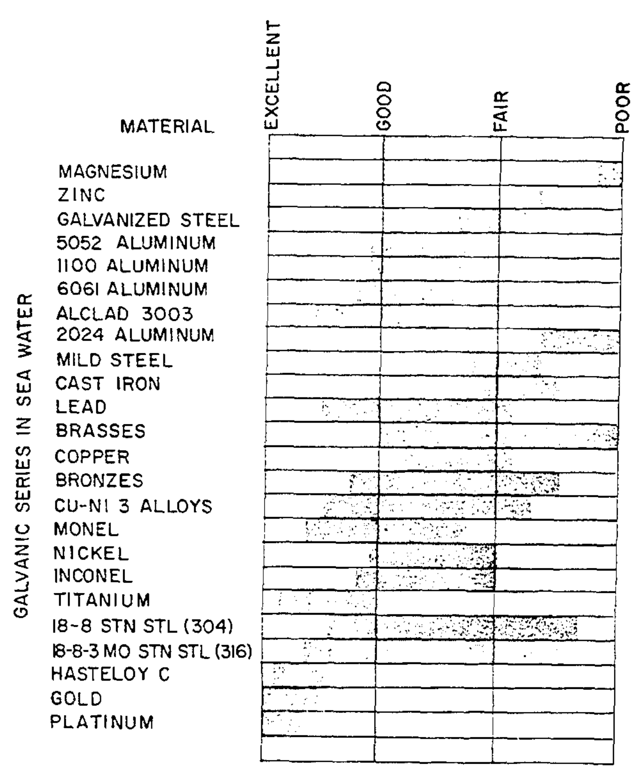

Fig. 9. Long-term corrosion resistance to sea water. (Evaluation is based on the author's judgment.)

aerated water gives excellent corrosion resistance, while the same material improperly joined (crevices) and in a low-oxygen environment will severely pit and corrode.

The following sections give brief descriptions of the more common engineering materials and their behavior in sea water.

Magnesium

Magnesium has no corrosion resistance whatsoever in sea water. Being the most anodic material in the sea-water galvanic series makes it a good sacrificial anode for galvanic protection of other metals.

Aluminum

Aluminum and its alloys show promise for applications in long-life oceanographic instrumentation. When left to corrode freely in sea water, aluminum will pit. A voluminous corrosion product, aluminum oxide, forms over the pit bringing on a "self-stopping" action. If the oxide spots remain intact, the corrosion will slow to a stop and the pitting will be superficial. In a high-velocity stream, the soft aluminum oxide will wash off and expose the bare metal, resulting in the rapid continuation of pitting and eventual penetration. The formation of a uniform, protective oxide coating is influenced by the amount of oxygen in the water. Deaeration has been reported to cause higher rates of corrosion.

The copper-based aluminum alloys (2024) show very poor resistance to the marine environment. They suffer from intergranular corrosion—corrosion which does not slow with time.

Copper and Copper-Base Alloys

Pure copper has the ability to corrode evenly without pitting when submerged in sea water. The rate at which the complex corrosion products go into solution largely depends on the amount of oxygen reaching the exposed surface. In still sea water the corrosion products linger, reduce the amount of oxygen reaching the surface, and subdue corrosion. In moving water the corrosion products wash away and accelerate the corrosion rate. The continued exfoliation of the copper surface is the basis for its famous antifouling properties.

Hundreds of copper-base alloys have been developed, but because of the lack of an enforced system of nomenclature, the whole area is one of confusion. The engineer is cautioned to specify clearly the material he wants by alloy content, not by name.

The copper-base alloys are broken down into four general types: (1) brasses, (2) bronzes, (3) cupro–nickel alloys, and (4) nickel–copper alloys. The brasses (copper–zinc alloys) have fair to good corrosion resistance if inhibited against dezincification, a serious form of corrosion in which the brass disintegrates as the zinc goes into the solution. The addition of arsenic to the alloy inhibits dezincification in some brasses. No inhibitor has yet been found for such common brasses as muntz metal and naval brass and these materials should not be used for sea-water service.

The bronzes are copper–tin alloys also containing other alloying elements such as manganese, phosphorous, silicon, nickel, or aluminum. Some alloys are sold with the name bronze, but contain zinc and are actually brasses and therefore subject to dezincification. In general, the bronzes have high strength and fair to good corrosion resistance. The brasses and bronzes, while susceptible to pitting, corrode with varying degrees of uniformity. The continual exfoliation of the surface discourages fouling.

The cupro–nickel and the cupro–nickel–iron alloys have fair to good corrosion resistance and are useful in higher velocity applications, 15 ft/sec or more, which would cause serious pitting of the brasses and bronzes, which rely on their lingering corrosion products for protection.

The nickel–copper alloys, called the monel metals, have excellent corrosion resistance in high-velocity and aerated sea water, but are highly susceptible to crevice and oxygen concentration cell type of corrosion.

Steel and Iron

Steel and iron are attractive as general construction materials because of cost and mechanical properties but they can be used in oceanographic instrument work only if the surfaces are completely coated. These materials corrode rapidly when exposed to sea water and are subject to severe pitting. Their corrosion rate is accelerated by the presence of oxygen. In a low-oxygen environment (e.g., buried in the ocean bottom), the corrosion is reduced considerably.

Stainless Steel

There seems to be a popular misconception about the anticorrosive powers of stainless steel. A large percentage of the more modern oceanographic devices, cables, and pressure cases are made of stainless steel. However, it is generally recommended among corrosion specialists that the long-term use of stainless steel in sea water be avoided. Stainless steels generally show only slight discolorations when exposed for long periods, but they suffer rapid pitting and are extremely susceptible to crevice and oxygen cell type of corrosion. The stainless steels can be cathodically protected but care must be taken to prevent hydrogen embrittlement.

Some of the stainless steels are more susceptible to corrosion than others. The 400 series is considered least suitable. They suffer from severe pitting and when cathodically protected they blister. The 300 series is generally more corrosion resistant with Type 316 considered to have the best corrosion resistance.

Titanium

Pure titanium has very good corrosion resistance to sea water, but depends on a passive film for protection. It is not as susceptible to pitting as the stainless steels. Little is known of the sea-water corrosion resistance of the titanium alloys.

Hasteloy

The Hasteloys are expensive nickel–molybdenum alloys. Grades A and B have moderate corrosion resistance in sea water. Grade C, however, is considered to be one of the most corrosive-resistant materials available.

Plastic Materials

There is little published information concerning the behavior of plastics in sea water. Only a few concerns have been interested in this field. Perhaps the greatest contributor has been the Bell Telephone Laboratories, involved since 1957 in a systematic investigation of plastics and related materials in connection with their work on submarine cables[16].

It has been found that the plastics undergo various degrees of decomposition in sea water due to the chemicals and living organisms in the marine environment. The rate of organic breakdown is quite slow for most plastics and the following list typifies the materials which will remain resistant for a number of years[15,16]

Polyethylene	Epoxies	Teflon
Gutta-Percha	Fiberglass	Silicone Rubber
Polyvinyl Chloride (PVC)	Lucite	Polypropylene
Neoprene	Nylon	

FOULING AND ATTACK

All of the 17 major phylogenetic groups of the animal kingdom and two of the four primary divisions in the plant kingdom exist in the sea. Only a small percentage of the tens of thousands of individual species represented are responsible for fouling, however. Although only 50 to 100 species are commonly encountered, almost 2000 species have been reported[2]. The fouling organisms are predominantly sessile (become permanently attached) and consist mainly of barnacles, tunicates, hydroids, marine plants, and bryozoa. Certain other species occur less frequently and the reader is referred to the Woods Hole Report on marine fouling[2] for a complete description of the fouling community.

The fouling organisms, in minute larval or undeveloped juvenile form, lie suspended in the water waiting for the opportunity to attach to a surface in order to live and grow. Ocean temperature is the major factor affecting the number of organisms present and their rate of growth. Marine organisms at or near the surface of the ocean have been observed to continually breed and thrive in waters of 30°C, the same environment becoming less favorable at 20°C, and below 10°C to markedly suspend reproduction.

Factors influencing the attraction of the fouling organisms to a surface include water motion, surface color and illumination, and gravity. Motion of the water relative to the surface (velocities exceeding 2 to 4 ft/sec) prevents the organisms from gaining a foothold. The organisms accumulate more easily on a horizontal surface than on a vertical surface and, with the exception of the plants, the fouling organisms are sensitive to light and illumination and prefer darker surfaces. In general, light-colored illuminated surfaces will be subject to reduced fouling, all other factors being equal[2].

The different groups of organisms cement themselves to submerged surfaces in different ways. For example, bacteria form slime films, algae exude a mucilaginous material which hardens, and barnacles and mollusks excrete a calcareous cementing material. When the organisms die these cements remain intact and some of them, especially the calcareous deposits, resist high velocities and mechanical scraping. The degree of adherence is determined primarily by the type of surface. In general, a hard smooth surface provides the best foothold.

The sequence of fouling begins almost immediately, first with the formation of bacteria slimes, and then by the development of algae and larger organisms. Within a week, under severe fouling conditions, fouling can become noticeable and within three weeks the surface can be completely fouled.

The amount of fouling decreases with depth. The fouling organisms encountered are also different. While at the bottom of the ocean extensive fouling has been reported on submarine cables and anchor chains, 25 ft above the bottom much lighter fouling has been reported. Figure 10 illustrates a very general fouling profile. The extent of each form of fouling is dependent on season and location. In coastal waters fouling is much more severe than in the open oceans.

Effects of Fouling and Attack on Materials

The attachment of mussels and barnacles stimulate the corrosion of materials. Most severe is barnacle gouging, illustrated in Fig. 11. The barnacle, as it grows, pushes its sharp edge outward. If it is resting on a soft coating, it also pushes downward. The barnacle can penetrate a soft thin coating and reach the metal surface, thereby promoting corrosion. Oxygen is excluded from beneath the barnacle and oxygen concentration cells can result.

The calcareous cement excreted by these organisms has a destructive effect on some paint films. Also, it adheres so tightly to these films that when the larger organisms, such as mussels, are torn from the surface (e.g., by feeding fish), a portion of the paint film may also be torn free, leaving an exposed area.

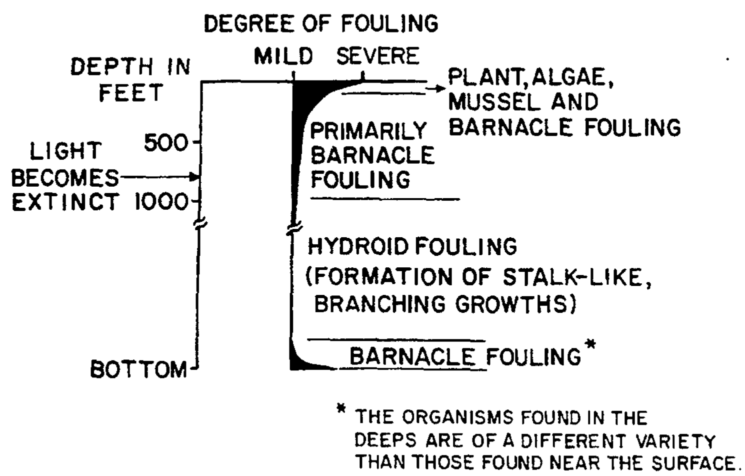

Fig. 10. A general fouling profile (degree of fouling *vs* depth). The extent of fouling indicated is dependent on season and location. The most severe fouling occurs in warm coastal waters [2].

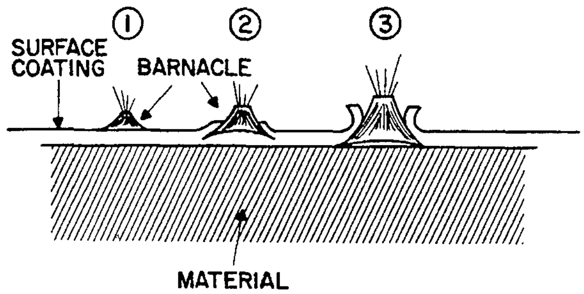

Fig. 11. Barnacle gouging. A young barnacle cements itself firmly to the surface coating (1). As it grows its sharp edge grows outward and downward (2), and with time may reach the materials surface (3), often promoting corrosion.

Marine borer attack presents a problem since the large variety of borers (e.g. the toredo borer) have the capability to penetrate almost any of the plastics. Deep penetrations in silicone rubber and Lucite have been reported[16]. However, the marine borers, boring for food or for protection, usually do not begin directly on the plastic surface. They like to get started in such materials as wood or jute or dense calcareous fouling and continue boring into the plastic material which is in intimate contact with the starting material.

Marine borers, while most active in coastal waters, where there is ample organic matter such as wood, have been reported at almost all depths.

Antifouling Techniques

The growth of animals and plants on submerged instruments and associated equipment is difficult to control. Two methods have been implemented with varying degrees of success. One is to continually bathe the instrument with toxics. The second method is to have the instrument's surface disintegrate evenly at a rapid rate (exfoliation), continually exposing a fresh clean surface. Pure copper, the best antifouling material available, provides both methods. Its surface corrodes quickly and uniformly and the copper ions formed are considered toxic to some larvae. Of all the engineering materials, only copper and the high-copper alloy have these antifouling properties.

There are many agents toxic to marine organisms, but unfortunately they are also toxic to man. The most promising of toxicants available today is called "Toxion"[17], an organo-tin salt developed in England which hydrolyzes to form harmless salts. The problem with the use of toxicants, however, is devising methods of releasing enough toxic for lethal concentrations, but releasing it slowly enough to prevent rapid exhaustion. This has been the challenge of paint manufacturers. To date, none of the modern antifouling paints will inhibit fouling for long periods; only two to six months of control is common. The majority of the paints are copper-base and care must be taken to isolate the paint from the metal surface to prevent galvanic corrosion. Heavy primer coats are available for this purpose.

The use of electric currents to prevent fouling has received some publicity. While it has not been found to repel or electrocute the fouling larvae, the galvanic protection resulting has caused exfoliation of the exposed surfaces thereby minimizing fouling.

SUMMARY

It has been shown that there are many factors influencing the selection of materials for long-life oceanographic instruments. Fouling appears to be the major problem affecting the useful life of instruments and no general solution can as yet be offered. Corrosion is less of a problem. Materials such as titanium and Hasteloy C, and some of the less expensive and easier to fabricate materials such as copper-base alloys and aluminum give promise for excellent long-life service if properly applied.

The oceanographic instrument designer confronted with the complex problem of choosing the best materials for particular application should consult corrosion engineers, marine biologists, and oceanographers before making a final choice of materials.

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DISCUSSION

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) I would like to compliment you on your paper, Dick, and I was wondering whether you might care to comment further on the addition of colored pigmentation to plastic cable material in an attempt to change the fouling characteristics? You gave the impression that it was perhaps absence of pigment that did the most good. I have heard it both ways.

A. Well, Jake, I have tried to understand the factors influencing fouling. One is color. According to the Woods Hole Oceanographic Institute it is strictly a lightness and darkness that makes the difference, and I have not seen any literature indicating that red, for instance, is better than green.

Q. In the case where a black pigment is added to white cable, would that prevent fouling?

A. It would reduce the rate of fouling because the cable would become darker. Here is an interesting fact. It is a popular misconception that you can electrocute fouling larvae by passing electric current through a piece of metal. As far as I can find this has not been verified. A metal can be caused to exfoliate, however, if a current is passed through it, thereby keeping the surface free of fouling.

Q. (Lee Dutton, Columbia University, Dobbs Ferry, N. Y.) I wondered if you have access to any information later than 1960. We have information that would contradict most of what was shown on the first four slides.

A. Concerning the ocean current, this is a good topic for discussion. I would be interested to see what you have for a current profile. In choosing this particular current profile, we have looked at specific currents in the gulf stream and all different parts of the ocean that we know something about. This particular curve is an accumulation of these data. (Mr. Dutton mentioned later that he had personally witnessed current measurements of approximately 6 knots at 20,000-ft depth.)

Q. (Joe Walentine, RCA Labs., Princeton, N. J.) I did not see chromium on your list of galvanic materials. Was there any reason for this?

A. No. I chose the more common structural engineering materials. Chrome is generally used as a plating material.

Q. (K. A. Allebach, Nortronics, Palos Verdes, Calif.) I wonder if this problem you are studying is not one that is the same that we have all been concerned with, except that you have a slightly better and a more universal electrolyte?

A. This is true. It is the same problem you have been running into when making magnesium assemblies, for instance. You have to use the same principles in selecting mating hardware. You wouldn't want to use stainless steel hardware in contact with raw magnesium, for example.

Q. (Bob Lomerson, Westinghouse, Newberry Park, Calif.) Two things: What would happen if you put something like copper sulfate in an epoxy? Wouldn't this tend to give you a retardation toward borers?

A. I don't know.

Q. Would it give them a toxic effect as they bore in?

A. I don't know whether it would kill them or not. I do know that the borers have been reported to have penetrated some types of epoxy.

Q. Have you ever tried stainless steel after putting a controlled chromic oxide surface on it? This is extremely resistant to almost any kind of oxidation chemical action. You can't even deplate it.

A. No, I have not. When a coating excludes the sea water and is abrasion-resistant, it can be considered very useful.

Q. The main thing about the chrome oxide is it can be easily put onto fairly thick surfaces and it is extremely resistant to abrasion.

A. That is the important thing. It sounds like a very good finish.

Q. (K. A. Allebach, Nortronics, Palos Verdes, Calif.) Some years ago I worked with a petroleum company in the pipeline division. We encountered pitting of pipes and this is perhaps an interesting commentary on the things you are speaking of. We found that these steel pipes would develop anodic points and would pit, and in some cases in a very few days would go completely through a pipe. The whole reason for coating the pipe was to keep moisture away from it.

A. Right.

Q. (D. A. Beck, Bendix Research, Detroit, Mich.) At what depth do you find this second tier of barnacles?

A. About 25 ft from the bottom, wherever the bottom may be. Just take the bottom and go up about 25 ft and this is the area where a concentration of fouling has been reported. Above that you get what is called hydroid fouling.

Q. Then from 25 ft above the bottom to the bottom you have these barnacles—is that right?

A. Yes, that is correct.

Q. Do you have any experience on large structures on the bottom, say, below 1000 or 1500 ft, for any extended period of time?

A. No. I have no information. I mentioned before that very little data have been accumulated on the behavior of materials at the bottom. The bulk of the data are from the Bell Telephone Labs and transatlantic cables.

Q. Most of the equipment is down there still being worked on?

A. Still being worked on—right!

Q. (Tom McCloskey, Motorola, Phoenix, Ariz.) I would like to know if your studies indicate that fibrous materials and/or composite materials, such as reinforced fiberglass, are more subject to fouling than a homogeneous material?

A. Any material which doesn't exfoliate is susceptible to fouling; the only difference then becomes the color. The fibrous materials run into a problem with barnacle gouging. If it is actually a fibrous surface, the barnacles can take hold and actually begin pushing the fibers apart. Every material that we know of, with the exception of the copper-base alloys and copper itself, fouls at about the same rate. The only thing that you can do is to put on paints which exfoliate or release poison in the area.

Q. (Harry Bendtsen, Paraplegics, Chicago, Ill.) Have you had any experience using a coating of Delrin in any form?

A. I haven't but I might venture a guess. Delrin is a hard plastic and it might behave very similarly to lucite as far as fouling is concerned. You can expect it to foul because it doesn't exfoliate. As far as the marine borers are concerned, I am not sure that it is hard enough to withstand them.

Q. It has a very lubricating type of surface in addition to being somewhat resilient. That is why I wondered if it would have any effect against the borer.

A. The marine borer usually does not start on a relatively hard material. If this material is wrapped in jute, for example, the borers will get a start and possibly penetrate. The material hardness appears to be the controlling factor in penetration.

Q. (Dan O'Neill, Grumman Aircraft, L. I., N. Y.) Do you find that mercury oxides have the same characteristics as copper, that is exfoliating?

A. Mercury oxide, if added to an exfoliating paint, can be effective.

Q. I have used a mercury-base paint on boats and have found it very effective.

A. Most marine paints rely on an exfoliation. If, at the same time, you can dispense mercury oxide, you can kill larvae and that is obviously what your paint is doing, besides exfoliating.

Q. (Bill Bowlby, Boeing Co., Seattle, Wash.) Do you have any information on the use of silicone alloy material similar to Dialect 1147? I ask this because of an application of a submarine radome and an antenna insulator which was made of this material. It is nonwetting and nonfouling, which allows immediate transmission because the water drains off. I was wondering if this would find any application?

A. I have heard some favorable reports about this material. It certainly deserves investigation.

A Unique Approach to Welded Packaging

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This paper will describe a packaging concept aimed at achieving component densities higher than with normal "laydown" techniques; providing for ease of engineering-change activity; automated assembly; and utilizing both welded and soldered connections. There was no direct attempt at miniaturization.

INTRODUCTION

THE BASIC CONCEPT of standing components on end *vs* laying them flat on a card is not new. The novelty is in automatically inserting components into a strip clip, welding the top component leads to the strip, and cutting the strip into "packs" for insertion into a card. This packaging concept is known as *STAN-PAC*®.

Standing components on end decreased the required mounting space by one-third to three-quarters from the laydown approach. A connective path between the tops of these components also provides an additional level of wiring. Since it was desired to use single-sided wiring, the crossover problem and the density of the etched pattern were either greatly minimized or eliminated. The reverse side of the card is sometimes used as a ground or voltage plane.

The first approach to mounting components reliably in this manner was to insert them into "pockets" in a plastic molding, the top leads being joined by welding to a nickel ribbon. The disadvantages of the method were the number of parts required, the length of the plastic molding, and blockage of air flow in certain cases. The design is shown in Fig. 1. After several minor design changes, the one shown in Fig. 2 was selected. This consists of a phosphor-bronze strip with clip mounting positions for components on 0.150-in. centers. The family of components included are: A-B $\frac{1}{4}$-w resistors, subminiature glass diodes, capacitors (developed for this program), feedthroughs, and insulated support units.

Feedthroughs are in effect 0-ohm resistors, comprised of a wire in a molded body. This component provides an electrical path from the strip to the card. Stanchions are insulated components which do not carry current, and are used merely for mechanical support.

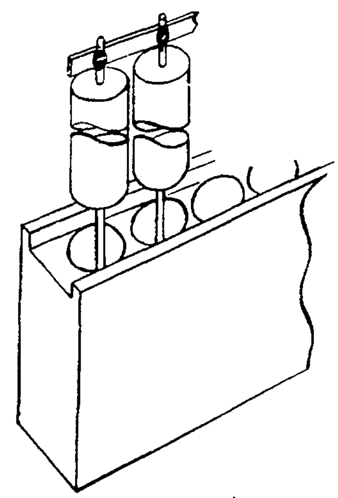

Fig. 1. Plastic component pocket.

COMPONENT AND CLIP REQUIREMENTS

This system requires that all components used in the strip be (1) of a common body size, and (2) have leads suitable for making a reliable welded joint.

Component size was based around the A-B $\frac{1}{4}$-w resistor and, as such, the size, tolerances, and general requirements are:

Length	0.225 in., min.–0.265 in., max.
Diameter	0.092 in., min.–0.108 in., max.
Alignment	0.010 in.
Concentricity of lead to body	0.010 in. TRI
Leads free of paint	0.060 in. from body, max.
Lead/coating	Copper with 90/10 Pb/Sn Copper with Sn Dumet with Sn

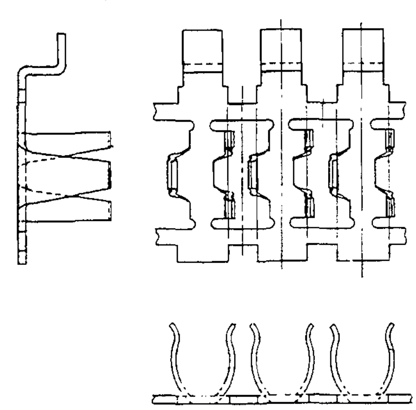

Fig. 2. Component mounting strip.

The tin coating of the copper varies between 0.00003 and 0.00005 in. The copper must be OEC for optimum results. No requirements are placed on lead diameters or finish, other than those supplied by the component manufacturer. The clip is made of 0.010-in. half-hard phosphor bronze with a 0.00004-in. plating of pure tin.

ETCHED WIRING CARD AND ASSEMBLY

The cards upon which the strips are mounted are 4.5 in. high and 5.35 in. wide. There are 32 nickel/gold-plated tabs, with the base stock being $\frac{1}{16}$-in. epoxy paper with 1-oz copper on one or both sides. The basic land pattern consists of 825 holes, 0.046 in. in diameter, on a 0.150-in. grid. Lands are 0.090 in. across the flats, allowing for a 0.020-in. wide conductor and 0.020-in. spaces. Wider conductors are used where required. Figure 3 shows a typical card pattern.

The basic 825-hole card is used for all assemblies, the circuit variations being controlled by the conductor pattern and the length and placement of the component packs. The only components on a card are transistors, decoupling capacitors, and the component packs. Provision is made for about 44 transistors (TO-18 case), although 27–32 is a normal count for a high-density layout. Approximately 330 other components may also be mounted.

A typical layout gives a component packaging density of 46,000/ft^3 based on the volume of the card itself (area $\times$ $\frac{1}{2}$-in. spacing). While this is not an exceedingly high figure, it does represent a significant increase over laydown components for this application and it may be readily assembled by hand or by automated methods. Also, it is economical and easily repaired, in addition to having been proved a reliable package. Figure 4 shows a card having a total of 280 components. Figure 5 shows the reverse side of the same card. Special diode matrix cards have mounted 813 diodes in this manner, for a component density per card of 121,950/ft^3.

Replacement of components in the strip is accomplished by snipping the weld tab and unsoldering the bottom leads from the circuit pattern. The new component is completely soldered in place, the top lead being bent to one side or the other to contact the strip prior to soldering.

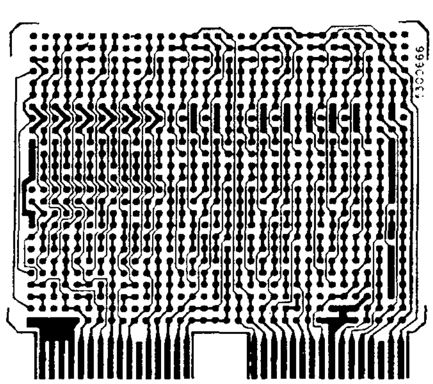

Fig. 3. Typical card pattern.

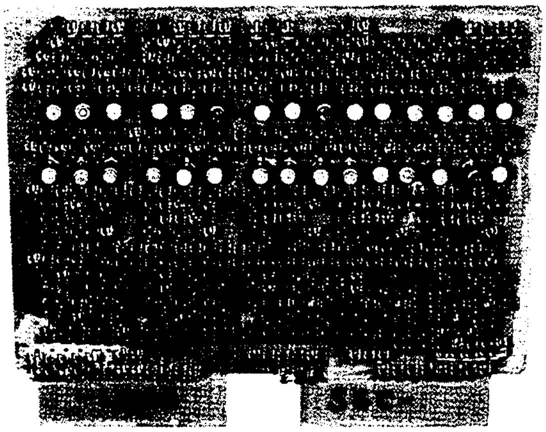

Fig. 4. Circuit card.

Some circuits require a higher degree of reference to ground, in which case a ground plane is etched on the reverse side of the card. Proper connection from the circuit pattern to the ground plane is achieved through the use of a wide strip, similar to the component strip. This piece has no clip positions in it, although "feet" are provided at the 0.150-in. centers. Such a strip offers low impedance and voltage drop. Figure 6 illustrates this strip and its application.

Tests

While initial tests showed no significant difference between plated and unplated phosphor-bronze stock, the use of an automated high-speed welder produced

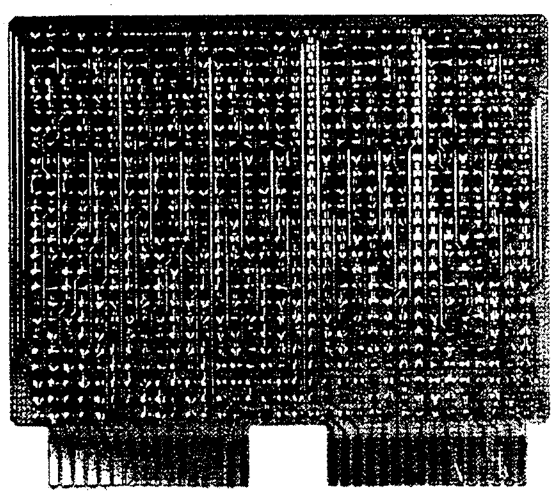

Fig. 5. Reverse of circuit card.

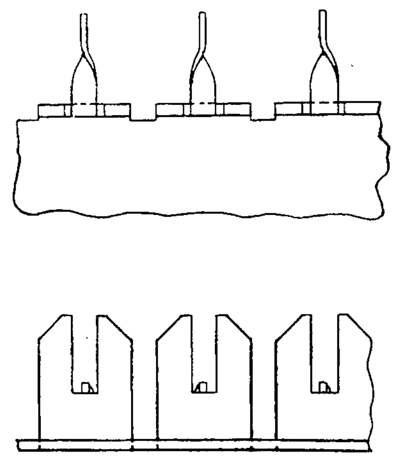

Fig. 6. Voltage bus strip.

more uniform results with the plated strip. The plating eliminates corrosion and/or discoloration of the bare strip.

During initial tests, various component lead materials, coatings, and sizes were investigated. Contrary to popular belief, gold/nickel or gold over copper, or other recommended weldable leads produced no significant improvement in weld quality over copper or tinned copper.

Since it was impossible or uneconomical to obtain the same lead material and size on all components, the variation was reduced to three: lead/tin-coated copper leads (resistors), tin-plated copper leads (capacitors, feedthroughs, stanchions), and tinned dumet (diodes). Process variables were adjusted to produce optimum results with these three types of leads used in conjunction with the plated phosphor bronze strip. Figure 7 shows a section of a dumet weld lead.

Calculations and actual heat measurements on the effects of welding and soldering within 0.060 in. of the component body showed no detrimental effects on several thousand components.

Soldering is done at 525°F for 3 to 4 sec as opposed to the normal cycle of 495°F for 8 sec. It was found that the component lead reaches solder bath temperature within 1 sec.

In welding, the actual heat rise measured at a distance of 0.050 in. from the weld area was 275°F as opposed to the theoretical figure of 12.6°F. This test was conducted on the phosphor-bronze strip using a 24-gage copper lead.

Much work has been done to find a method to measure reliably the quality of the weld joint. It can be said, in general, that if the mechanical strength is good, the electrical joint is good.

One method which shows promise of determining a good weld is to measure the voltage drop across the weld. Variables such as differences in lead size, composition, and surface condition are being investigated to substantiate this concept further. It should be pointed out that no set of data should be taken at face value for all applications. Tests must be conducted to find the optimum parameters for a given design and application.

Fig. 7. Dumet lead welded to Phos Bronx strip (180×).

This packaging project, now in use, has substantiated many of the claims made for welded construction (cleanliness, connections in limited space, metallurgical connections, and the capability to be highly automated). It also has disclosed some of the basic fallacies in welded programs (copper/copper alloys can be welded reliably, component parts can have fairly wide tolerances).

The entire assembly is provided protection during final test, and shorting of components to adjacent cards when inserting and removing cards from the machine is eliminated by use of a molded nylon cover. Nylon was chosen because of its toughness and ability of flow through thin mold sections, the top cover being 0.028 in. thick. Figure 8 shows a card/cover assembly. Quality-control figures indicate 0.1–0.3% weld defects in the automatic process. This is based on 350,000 or more welds per week on a production basis.

AUTOMATED STRIP ASSEMBLY

The preceding portion of this report was devoted to the engineering development of this project and the various approaches associated with this welded package. As important as this development phase may be, however, its true significance is determined by the degree of ease or difficulty experienced by the manufacturing engineer upon releasing the item to production. Obviously, successful laboratory models or prototypes are not truly indicative of the manufacturability of the item. That test is made during the development period when practical manufacturing methods are introduced. The welded package under discussion here represents the end result of effort by a team comprised of development and manufacturing engineers.

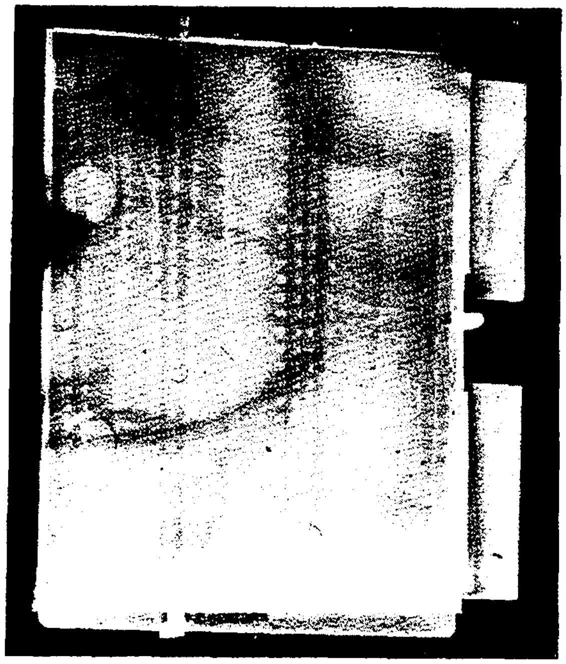

Fig. 8. Card assembly with cover.

The component-to-strip assembly machine was designed and built to meet the specific demands of the Stan-Pac welded package. Three major factors were considered in its initial design and justification. These factors were related basically to the manual aspects of the component-to-strip assembly and the weld operations.

Manual Handling of Miniature Components

In this package, the small $\frac{1}{4}$-w resistor-type tubular components do not facilitate manual-assembly operations such as selection, grasping, positioning, and welding. The application of manual tools would improve the operation to a small degree but not to the optimum level desired.

Manual Assembly Errors

Inconsistent assembly errors such as incorrect component location on the strip, reversed diode polarity, and missing welds were experienced during the prototype card assembly phase. This was indicative of the need for positive programming, which can be realized through automation.

Economics

A reasonable return on a major investment of this type requires a complete analysis of both the tangible and the intangible benefits. The results of an economic evaluation of the component-to-strip assembly machine, when weighing all factors, indicated that a favorable return was possible.

In the final analysis, the greatest factor influencing the success of this machine was our capability to procure these small tubular components within the specified physical tolerances. A greater range of dimensions on the length and diameter would obviously require more flexibility in the machine's sensing-and-locating features. If it is assumed that the machine-design problems attributable to the variation in component dimensions are solved, then designing a suitable clip is more difficult, imposing new problems and perhaps necessitating a complete revision of the process and related machine features.

It is understandable that the addition of special features and controls to accommodate a wide range of tolerances and materials possibly could render the project economically unjustified. Therefore, by maintaining restrictive tolerances on the components and materials without radically increasing component cost, it was possible to produce a successful automated process.

Machine Performance Specifications

The component-to-strip assembly machine is a fully-automatic process having high production capabilities. It was designed and built by the IBM Manufacturing Engineering Division, Poughkeepsie, to operate at an average speed of six clips per second. All operations are linked mechanically to ensure accurate timing. It will assemble any pack variety with as many as 20 different tubular components, such as diodes, resistors, and capacitors.

The process selects miniature tubular components from a group of 20 reels and delivers them within 300 msec to a position where they are inserted into clips on a continuous strip. They are subsequently welded to the clip, and then wound onto a storage reel.

An eight-channel coded paper tape is used for programming the various operations. This includes proper component selection and exact orientation into clip, identification of the individual packs, and adjustments in the weld unit to compensate for various lead materials.

Machine Description

Viewing the machine from the front (refer to Fig. 9) it is approximately 18 ft wide, 5 ft long, and 7 ft high. It is of modular construction, utilizing standard IBM cube modules and covers. This type of construction permits the addition or subtraction of auxiliary units to the process without affecting the main operating unit.

The process direction is from left to right. The left half, comprised of the strip feed and weld units, is detachable from the right half. The right half houses the main operating unit which performs the principal assembly operations.

Programming

Programming is conducted by an eight-channel coded paper tape. A standard IBM tape reader and standard punch alpha-numeric codes are used exclusively.

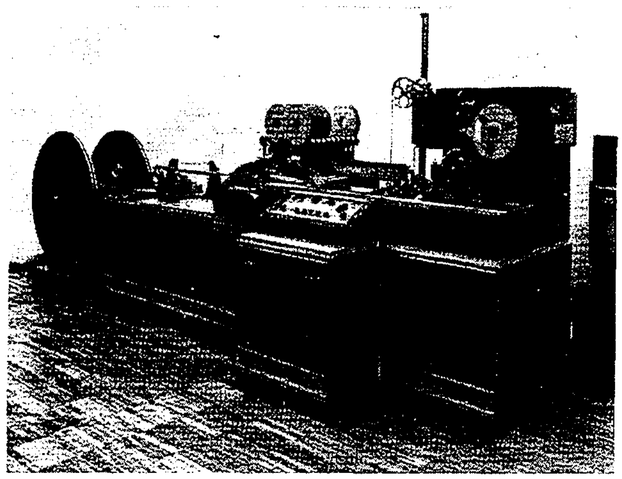

Fig. 9. Stan-Pac component-to-strip assembly machine.

The Stan-Pac card production drawing is the primary source of program information. The alphabetic code is used to describe components and the numeric code is reserved for welder control and card finish.

Program Controls

Programming controls the following four basic machine functions:

1. Cut component by actuating the single-revolution clutch at a particular cutoff station.
2. Set up trim punches for correct strip punching, including pack identification.
3. Actuate correct welder control to suit the component.
4. Card production counters.

Machine Timing

Each index represents one clip displacement. Two columns on the eight-channel coded tape are read for each index. The first column reads component selection, end of pack, and trim-punch information; the second column reads welder information and end of card. Absolute timing control is assured by coupling the tape reader directly to the main drive shaft. This same shaft drives the trim punches, welder, and a bank of cammed circuit breakers. Indexing is accomplished by a Geneva drive mechanism.

There is no memory in the system, as to input commands, and each column of information is acted upon immediately when read out by the tape reader in the first and second halves of the indexing rotation.

Assembly Process Description

The assembly process illustrated by Fig. 10 represents the total card-assembly

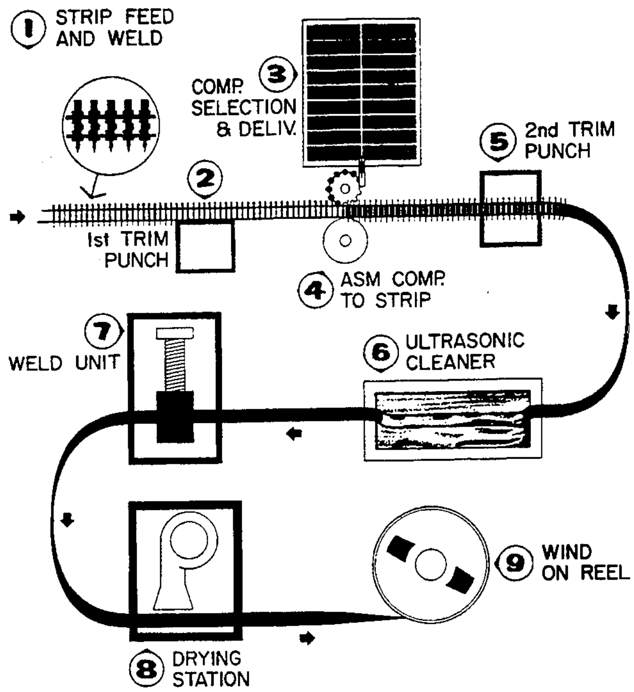

Fig. 10. Assembly process description.

operations established during the development stage of this program. With knowledge of such factors as component tolerance limits, variety of materials to be welded, material surface contamination, and program identification for further assembly operations, our Manufacturing Engineering group designed this machine with the flexibility necessary to cope with these variables. We shall discuss the process as originally designed into the machine:

1. Strip feed and weld.
2. First trim punch.
3. Component selection and delivery.
4. Assemble component-to-strip.
5. Second trim punch.
6. Ultrasonic clean (cleaning station facility).
7. Weld.
8. Dry.
9. Wind strip on storage reel.

STRIP FEED AND WELD UNIT

The strip in Fig. 11 is purchased on $10\frac{1}{2}$-in. reels and made up of random lengths and tracks. To make it usable for the process through the main operating unit of the machine, the strip must be unwound, joined together, and rewound on an operating spool. These operations are accomplished by the strip rewind unit.

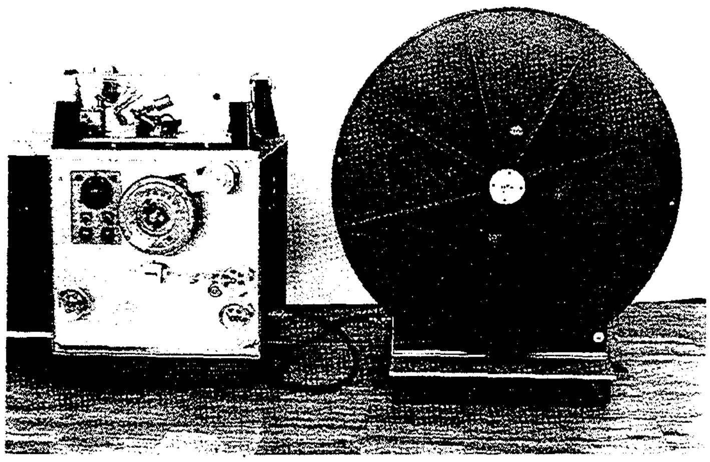

Fig. 11. (Backview) The strip is unwound from the small reel through check points which sense any breakage. It is then wound on the larger 45-in. reel. Transfer of 45-in. reel from the rear preparatory position to the front feed position is done manually. The weld, coin, and trim units are mounted on the module top plate.

As the strip is unwound from the smaller reel, it passes through a weld-and-trim station where the ends of adjacent strips are welded together, coined, and trimmed, then wound on a 45-in. single-track reel. This process permits continuous feeding of strip to the machine. Similarly, the ends of the strip from the 45-in. reels are joined together to avoid rethreading the machine and interruption of the main operating unit.

Cutout switches coupled with the main operating unit stop operations in the event of strip jamming or breakage. Under normal operation, the 45-in. reel, containing about 90,000 clips on 1125 ft of strip, will supply the main operating unit for 12 hr before replacement is necessary.

First Trim Punch

Progressing from the rewind station, in Fig. 12 the strip is shown fed into a trim punch. This punch, driven directly by the main drive shaft, removes the strip foot and pierces a small hole in the clip for pack identification. During this phase of the cycle, the desired component is cut from the taped reel and transported down the delivery chute toward the sprocket. The component and clip will eventually marry at the index station.

Component Selection and Delivery

When the first column on the tape is read, the information is sent to the decoder which selects the cutoff unit and picks the single-revolution clutch. With the clutch chosen, the component cutoff punch is actuated through a crank shaft, cuts the component from the taped reel and injects it into the delivery chamber

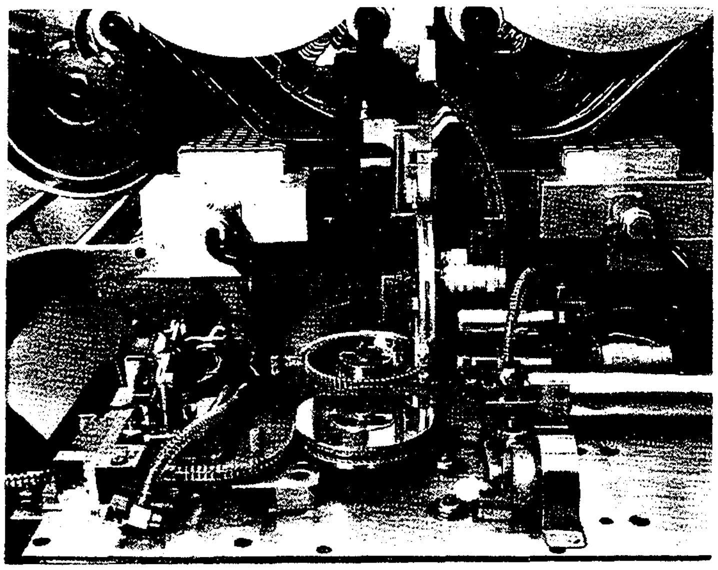

Fig. 12. Leaving the delivery chamber, the component changes to a vertical position on its downward travel in the curved chute. The cover plate is raised to show typical component position. The assembly of component to strip is accomplished by the two horizontal sprocket wheels in the foreground. On each side of the sprocket wheels are located the trim punches.

(see Fig. 13). On the return stroke, the next component is positioned in the cutoff station ready for the next cycle.

As the component enters the delivery chamber, it is carried forward on streams of air injected through small directed tubes. Air pressure is used to control the component position near the bottom of the chamber, and to permit it to travel forward on a thin cushion of air. The component velocity at the delivery shute will be as high as 61.2 ft/sec for the most remote component, and 3.3 ft/sec for the nearest component.

A curved chute at the end of the delivery chamber shifts the component from a horizontal to a vertical position. On its downward flight, the component drops into the vacant pocket on the periphery of the sprocket. A photoelectric sensing unit detects the presence of a component and signals the controls that this portion of the cycle is complete. The next cycle is initiated only after the welder has successfully completed its operation and other control conditions are satisfied. The display panel shows the complete phases of a cycle such as component cutoff and weld, as well as possible trouble indications. If any malfunction occurs, the machine shifts to manual operation. All operating controls, except auxiliary functions, are high-speed solid state devices.

Under normal operating conditions, the component which has dropped into the sprocket will move in a counterclockwise direction carried by the sprocket to a position displaced approximately 270°, where it is rolled securely into the strip

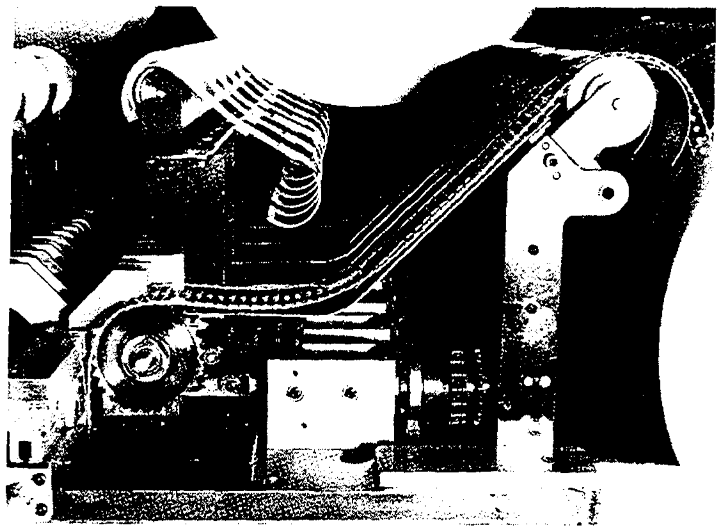

Fig. 13. Twenty different component reels are mounted above the delivery chute and cutoff units. A single-revolution punch under each reel activates the cutoff die to separate the component from the taped leads and insert it into the delivery chamber. The next component is readied at the die station on the return stroke of the cutoff punch.

clip. The clips have sufficient resilience to retain and hold the component in position throughout its journey to the welder.

The reels which contain the miniature components are prepared separately by an auxiliary taping machine. It is important that the specified spacing between components be maintained for assembly timing. Each reel will hold approximately 6000 components of the dimensions specified for this package. The reels are supported on their rims and rotate on a set of serrated rollers. The action of the cutoff punch as it returns to its original position causes the reels to rotate in the component-feed direction.

Second Trim Punch

A second trim punch, Fig. 12, connected directly to the main drive shaft trims the excess component leads at the tops and bottoms, in relation to the strip, to maintain a positive overall pack-height dimensions.

Ultrasonic Cleaner

Prior to welding, both the component and phosphor-bronze strip must be cleaned to remove any foreign matter that may contribute to a poor weld. For this purpose, a commercial-type ultrasonic unit (Fig. 14) is used to vibrate a warm detergent solution. The temperature setting is 110°F and the frequency is 27 kc.

The strip is suspended horizontally in solution a distance of 16 in., the approximate tank width. It is supported at the entrance and exit by the strip-guide wheels.

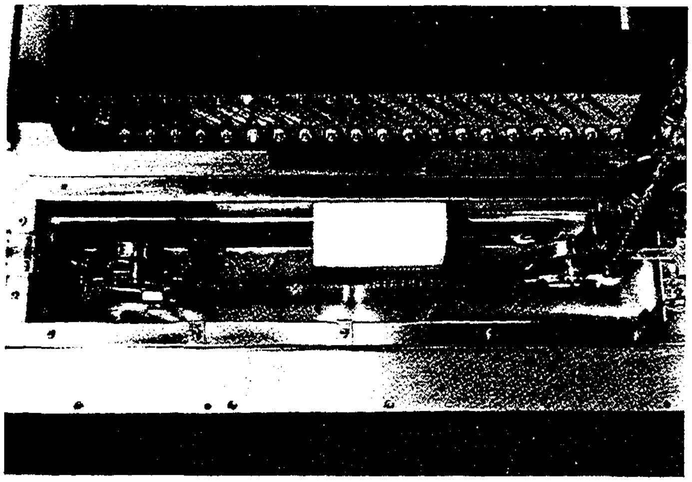

Fig. 14. The strip assembly is cleaned by an ultrasonic unit using a mild detergent solution. Water level is controlled by the white styrene float. The wheels at each end of the tank maintain proper tension and directions as the strip moves from left to right. The display light panel is discernible above the cleaning tank.

Water level is controlled by a styrene-float type of valve; a heater maintains uniform water temperature; foreign matter is removed by circulating the solution through a filter. A jet of air at the exit of the cleaning tank removes excess water. However, some water will remain on the strip by virtue of the low surface tension. Under normal operating conditions, a component will remain in solution for approximately 90 sec, that is, the travel time for a single component from one end of the tank to the other.

Located ahead of the weld unit is a strip take-up column which is manually adjustable to compensate for various strip lengths corresponding to equivalent card units between the delivery chute and the weld electrode. A card unit is the physical strip length required to populate a card. Safety switches on the columns provide check points in the event of a broken or jammed strip. The strip moves around the column take-up wheels and enters the weld unit with the weld tab forward.

Weld

The weld unit, Fig. 15, consists of an IBM-designed low-inertia, high-speed, welding head with a modified Taylor Winfield control and transformer. The component lead materials are copper and dument with 100% tin or tin–lead plating, such as found on standard commercial resistors. The strip material is phosphor bronze with 100% tin-plating. All welds are made under water to extend electrode

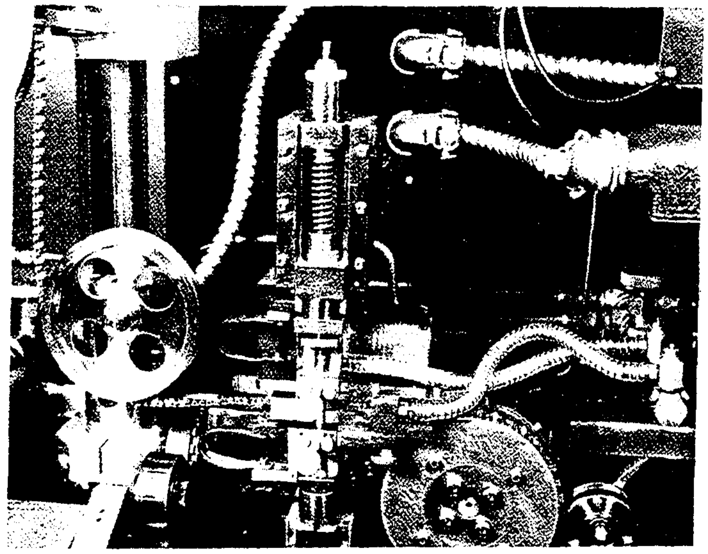

Fig. 15. One component lead is resistance-welded to the tab between vertical electrodes. The welder is programmed to adjust automatically for variable lead materials. A water coolant is supplied to the electrodes through two clear plastic tubes (right center).

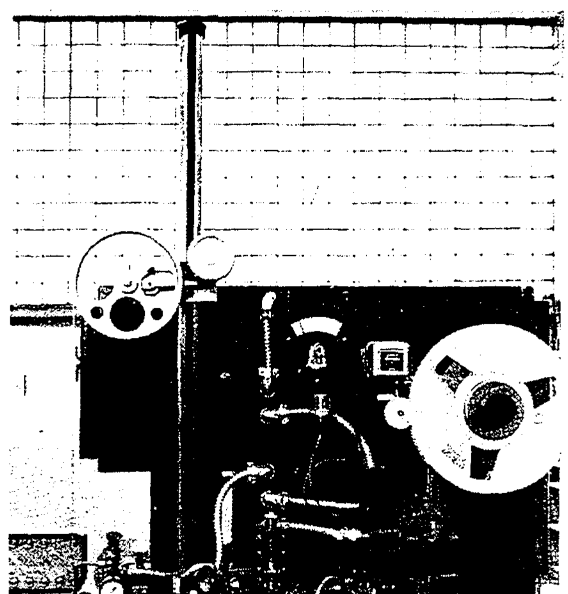

Fig. 16. The weld unit in the foreground is located between the take-up column and the heat gun. Welder controls are housed in the cabinet in the background.

life by providing coolant to low-mass electrodes. The welder is programmed for multiple-heat settings, while the actual weld time ranges from 3 to 7 msec.

A lockout circuit is employed to sense the electromagnetic field of the welder secondary cables; unless a field is present the machine will not index to the next operation.

Dry and Storage

After welding, the strip assembly continues toward the end of its process. It passes under a heat gun for drying and is then wound onto an IBM standard tape reel for storage and later processing (Fig. 16). The storage reel capacity of components and strip is equivalent to 10 or 15 cards, depending upon the component density. It also affords a controlled environment during storage. Figure 17 shows the strip assembly on a standard IBM tape reel.

DISCUSSION

Through continued engineering effort while the machine was operating on the production floor, a few further refinements were made which resulted in direct improvements to the process. For example, by modifying the locating features and programming techniques planned for further assembly operation, it was possible to procure the chain strip without the feet, thereby eliminating the need for the first trim punch.

The ultrasonic cleaner was designed into the process to provide the welder with clean and weldable strip and component leads. In solving this problem, however, another of greater severity was created. It was found that the optimum frequency level of the ultrasonic vibrator destroyed a particular diode by fracturing

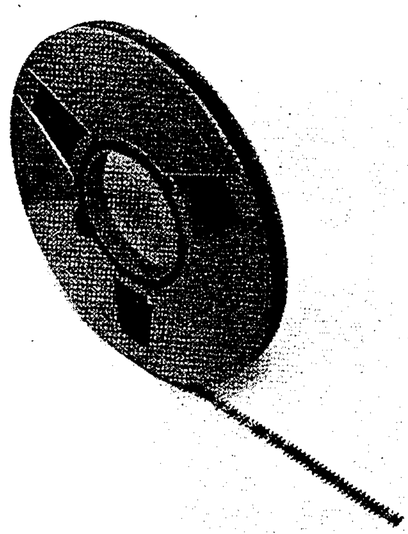

Fig. 17. The standard IBM tape reel provides an ideal storage medium and facilitates handling for further processing.

the internal element. Apparently, this diode was more sensitive than the diodes previously processed through the machine. In order to correct this condition, the strip cleaning operation was removed from the machine and transferred to a separate phosphor-bronze cleaning and protective process. After cleaning in a Metex solution, the phosphor-bronze strip was tin-plated, simply as a corrosive-resistant measure. Otherwise, without a protective coating, the strip would be subject to corrosive elements detrimental to the weld process.

A proper balance was obtained between the degree of flexibility built in a mechanical process and the magnitude of the financial exposure tolerated by the program. The component-to-strip assembly machine embodies basic operations integrated in the design which permits maximum flexibility at minimum exposure. It was noted above that through further engineering and refinements, certain operations of the machine were eliminated without affecting the process or function of the machine. In this case, it was less difficult and less costly to remove operations from a mechanized process than to add new operations.

ACTUAL PERFORMANCE

The Stan-Pac strip-assembly machine has been producing strips on a production basis for about one year. Certain commercial computers being shipped daily place a demand of approximately 1.5 million welded joints per month from the machine. This is accomplished at an average process rate of two components per second.

The quality and repeatability of the automatic process to date has accounted for 99.8% successful welds. Optimum weld conditions are quite difficult to obtain when considering the wide material-specification range of component leads. Common copper leads with tin–lead plating will possess a wide range of tin–lead compositions as well as plating thicknesses. These variables all contribute to the complexity of obtaining an optimum controllable welded joint.

Acknowledgment

The authors acknowledge the assistance from these engineers who were responsible for the success of this program: Mr. L. J. Allen and Mr. W. J. Richardson for their general engineering development work; Mr. T. J. Cochran, responsible for the mechanical engineering of the assembly machine and overall direction; Mr. T. R. Frederickson for his ingenious electrical engineering contribution to the machine; and Mr. A. W. Rzant, for his contributions to the welding portion of the machine.

DISCUSSION

Q. (Jay Block, Hughes Aircraft, Culver City, Calif.) With regard to your components, have you tried to achieve any type of a standardization of lead material to ease your welding problems? Have you tried to standardize on dumet or any one particular type of lead material?

A. No, we use standard lead material as the vendor supplies it. The Allen Bradley is a 90–10 lead tin over copper. The feedthroughs, stanchions, and capacitors are pure tin over copper and the diode is a tin dumet. We found that with proper control there was no additional lead preparation needed whatsoever.

Q. (Joe Guthrie, Engineered Electronics Co., Santa Ana, Calif.) Do you find that differences in lead diameters hurt welding?

A. Lead diameters make no difference. I will qualify that and say that the one phase that I can't talk about is the design and precise function of the weld head itself. In the beginning, this was in 1959, the biggest problem we had on lead diameters was not the lead diameter *per se* but the unevenness of tin lead coating (nodules, etc.). Since then Allen Bradley has cleaned up the process considerably; they have used oxygen-free copper and we haven't had any problems.

Q. (Dean Joachim, Univac, St. Paul, Minn.) I noticed that you utilized a nylon cover to insulate adjacent cards. I believe that this is placed over the components; in which case, how do you provide for adequate cooling for these components?

A. You are right. The addition of this cover reduced air-flow about 2%. This air flow reduction did not adversely affect the components or machine function as a result of temperature rise.

Q. (Martin Camen, Bendix Corporation, Teterboro, N.J.) I have a number of questions. First, one of the major aims of the program was supposedly to attain higher densities than the normal layout type. You gave a number of 46,000 parts. You also say that this is significant. Could you be more explicit? What do you mean by significant—in order of magnitude?

A. As I explained, the SMS card was a single card; the whole concept of the SMS was automated production. In order to get this, these cards have very few components on them. The average, however, was about 7000/ft^3, and this figure was derived from the outline of the card plus the thickness, determined by the socket spacing. Therefore, from a jump of about 7000 to 9000 we went into other two-time-size cards and by various techniques kept building this up. Some of the Stretch machines use a double-deck affair on components. These got up to around 18,000 to 22,000. This came along and got up to 47,000 and the one diode matrix that I mentioned was something like 123,000/ft^3.

Q. What figure of merit are you using for standard layout cards?

A. Let us compare it to a lay-down type component, which would have components on hundred thousandth centers, and on that you really gain here by this second level, wiring because of the strip itself. This picks up a considerable amount.

Q. Well, I feel to the contrary. We are using standard layout boards for breadboarding our digital computers and your figure of 50,000, I feel, is not significant compared to what we are using just in the laboratory for layout.

A. One must consider the economic aspects.

Q. Forgetting about economics here . . .

A. Let us say the whole card concept here is completely automated. From the sketch that a designer throws into the computer he gets records and tapes which follow this card all the way through the records department, the layout of the card, the design of the card, the placement of all parts, and into manufacturing. There are some cards that are sparsely populated; and I would like to mention one thing, which I think has a bearing on the entire Symposium. I don't think any of you should walk away from this Symposium, or any other, with the expectation that "Boy, this is going to solve all my problems." This is a place for ideas and concepts. I wouldn't want you to take any of the figures I gave you and expect you to go back and duplicate any of these things. I think there are plenty of ideas around and you have to adapt them to your application. In our particular application I can say that we did double the component count.

Q. I would like to go on to the next question. You make some pretty strong statements about popular belief and fallacies. One is and I quote, "Contrary to popular belief, gold nickel or gold over copper or other recommendable weldable leads produce no significant improvement in weld quality." Would you please define what you mean by weld quality?

A. Initial stages of the program used all of the components and lead materials available and the literature, which said if you do this and this, you will get this kind of result. Let us take an Allen Bradley resistor, for example. Who would have thought a couple of years ago you could go out and take a tin lead resistor off the shelf and make a reliable weld from it. You went to Allen Bradley and they stripped tin off and they put nickel on and then put gold on. I guess this has occurred with all component manufacturers. Everyone wanted a lead material which they thought was best. We ran through all of these. They were gold-plated, nickel-plated, all various thicknesses and in the end result, (economics again) the premium of about 10 to 15 c apiece on resistors didn't warrant it. I am not saying that with our present system we are getting anything vastly superior to what could be done if you want to really optimize it, but there is a breakoff point.

Q. The point I am trying to get at is essentially this: at Bendix in Teterboro we are engaged in an extensive welding program and I think we went through the same study program that you people did. We were greatly concerned over lead material. Now, all the studies that we have conducted and all the data point to a definite, significant improvement of weld quality using dumet leads or nickel leads as compared to copper leads.

A. You are free to come to Poughkeepsie and watch this machine in operation at any time and the only thing I cannot discuss is the weld head.

INTERCON—Prefabricated Weldable Circuitry

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This paper describes a prefabricated weldable circuitry, Intercon, capable of use at all three packaging levels. A series of figures illustrates the various applications of Intercon.

Little need be said of the advantages of welded circuitry over other methods of interconnecting electronic components, as we are all well aware of them. However, there are some disadvantages to the point-to-point wiring techniques used in welded circuitry. They are high labor cost, possibility of human error, and difficulty of keeping leads separated during the assembly operation. These difficulties gave rise to the development of Intercon. Intercon was developed to combine the reproducibility of printed circuitry with the reliability and miniaturization possibilities of welded circuitry.

As far as we know, Intercon is the first prefabricated weldable circuitry that can be used with all levels of packaging. It is used at the module level, either three-dimensional cordwood type packages or two-dimensional packages with components on one or both sides of a single board. In two-dimensional packaging, the ability to use both sides of a board increases the component packing density to the point where it is to some extent competitive with three-dimensional packaging and it frequently permits the use of standard connectors. Intercon is used for interconnecting modules whether or not separable connectors are used. Since the technique is not limited to rigid boards, one piece of circuitry may be used to interconnect components into a working circuit and to make the terminations into a connector without using additional wiring.

Simply stated, Intercon is a method of holding conductors in a predetermined pattern with tabs extending from the plane of the circuit so that component leads or other conductors may be welded to them. Electrolytic nickel is used as conductor material for most applications; however, in applications where high conductivity is required, electrolytic grade copper plated with one-half to one mil of nickel is used.

A variety of plastics is used, depending on the application. Normally the circuitry is embedded in glass-reinforced epoxy. Where flexibility is required, the circuitry is sandwiched between layers of polyester film that has been punched to the necessary hole pattern prior to assembly. This enables us to bring the tabs out on either side of the circuit layer where necessary. When a high degree of accuracy of hole location is needed for flexible parts, the circuitry may be bonded to a 3- to 5-mil-thick epoxy glass laminate. When the packaging concept demands it, the tabs are extended over the edge of the board; for instance, tabs or circuit extensions are frequently used to make direct connections to connectors with no intermediate wires, thus eliminating at least one weld per pin connection. Dimensions of boards and conductors are largely decided by the customer, however, the thickness of the board must be enough to embed the circuit plus 4 or 5 mils for glass cloth. The conductors may form 1-mil thick and 4 wide to 10 thick and unlimited width. The tolerances for conductor width and thickness is $\pm 10\%$. Now, with these parameters established, let us look at some pictures of typical circuits.

These are a few of the applications where Intercon has been used, demonstrating the flexibility of the technique. Seemingly, it is only limited by the ingenuity of the designer.

Now, how do schematics develop into Intercon boards or circuits? Generally speaking, the customer makes his component layout and then a wiring layout. These are sent to us where they are converted to Intercon layouts. Artwork is made and photographically reduced, similar to standard printed circuit techniques. The photography is inspected, touched up where necessary, and sent into the shop and the circuits are produced. Tooling is roughly equivalent to the tooling for printed circuitry. After prototype parts have been made, it seems desirable that the customer do his own layout and artwork, and we have complete layout and artwork instructions available. As is well known, it is frequently less time consuming if the circuit designer is located near to the layout man, because questions frequently arise as to whether minor changes may be made, and these questions can be resolved at once. When someone is beginning the design of a number of modules, it is desirable for him to send a designer to our plant for a few days so that he may become familiar with the process and the layout parameters.

We do not profess to be experts in welding, as our business is to supply circuits for the customers to assemble, however, our corporate research and engineering laboratory has made a study of the metal used in Intercon *vs* the nickel ribbon used in conventional point-to-point wiring. Comparisons were made of tensile strength of welds, resistance of the metal, resistance of welds, increased resistance due to bending of the tabs, and ductility.

The tensile strength of a good weld is always greater than the tensile strength of the weaker conductor joined, substantiated by the fact that the weld does not break during tensile tests. The resistance of wrought ribbon measured 0.103 ohms for a 2-in. piece of 0.005×0.020-in. ribbon; an equivalent piece of our conductor measured 0.102 ohms. As is well known, the resistance of welds varies little between good welds and poor ones. Calculations were made of the theoretical resistance of the conductors joined and measurements were made. The difference was no more than 2% which is in the noise level of measurement. One of the things that we were concerned about was the possibility of increased resistance due to the bending of tabs. Measurements failed to substantiate these fears as the resistance increased by no more than 2% from unbent nickel to failure for both our nickel and wrought nickel. Ductility tests indicated that wrought ribbon was about 20% better than our circuitry; however, quality control specs call for a minimum of three and one-half bends; about a radius equal to the thickness of the conductor. This is much more cold-working than can be expected in practice. These tests all indicate that the nickel used in Intercon compares favorably with the nickel used with point-to-point wiring.

What are the advantages of Intercon? Since controlled size conductors are embedded securely in plastic, they are mechanically and electrically stable, eliminating the variation in spacing possible with point-to-point wiring; it is applicable to all levels of wiring in present day miniaturized packages; and it is a prefabricated wiring technique that can help packaging engineers build smaller and more reliable packages.

As shown in the pictures, we have built a variety of circuits for numerous customers. Undoubtedly many other applications will be developed to help you solve your problems.

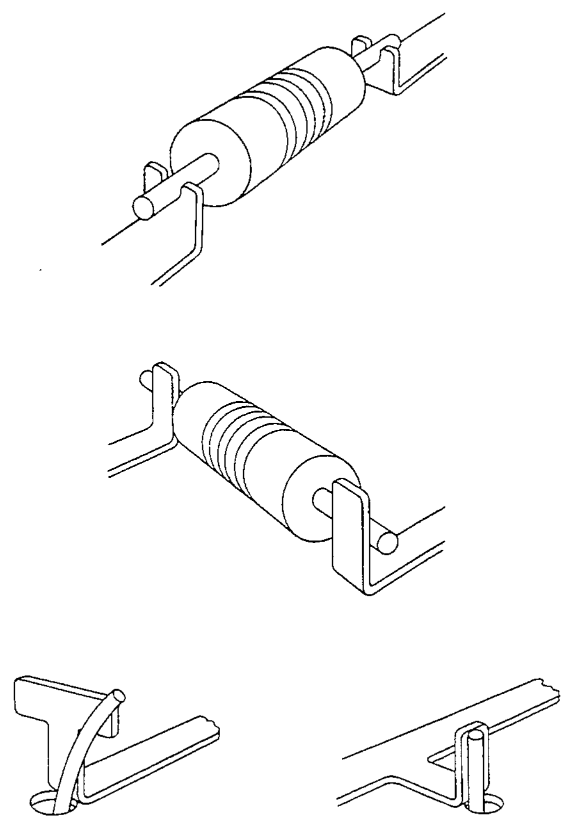


Fig. 1. The really unique thing about Intercon is tabs. So before we look at circuits, it might be well to see the various types of tabs that can be used. The inverted "L" tab is used where more than one weld may be needed on one tab. The conductor may be welded to the end of the "L" and if it needs to be replaced, it may be clipped off and a new weld made to the remainder of the tab. The straight or standard tab is used where lead comes through the board and is welded to the tab. Inline tabs are used on a two-dimensional board offering the possibility of reducing costs by partially jigging components without the necessity of putting leads through holes. The notched tab may be used for solder applications providing a means of locating components without having to bend leads or put them through holes.

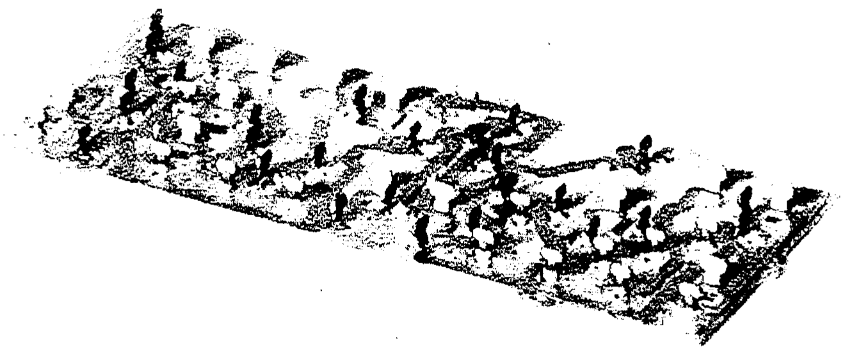


Fig. 2. This board shows another type of tab, the "T." It may be used where a wider target for the welder is desired. It also offers the possibility of multiple welds on one tab.

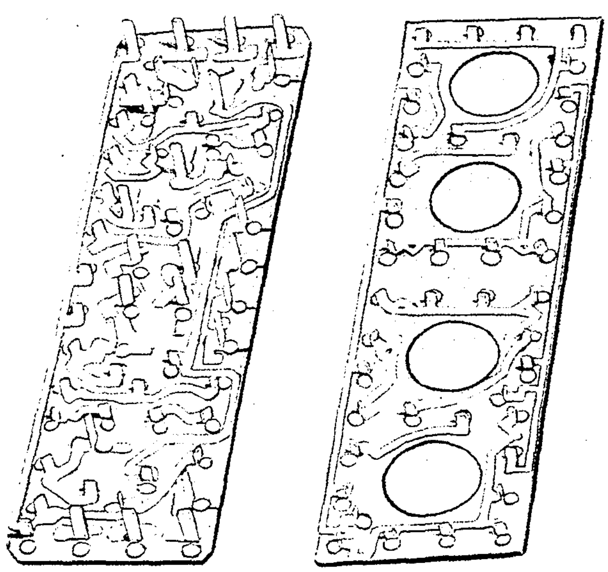


Fig. 3. The module that uses these boards is high in component density and fairly high in wiring density. The large holes in the lower board are used to position transistors. The short tabs are used to connect components. The long tabs are used to connect components and to communicate with the outside world. In other words, they are vertical conductors of a consistent thickness that are used for intermodule connections.

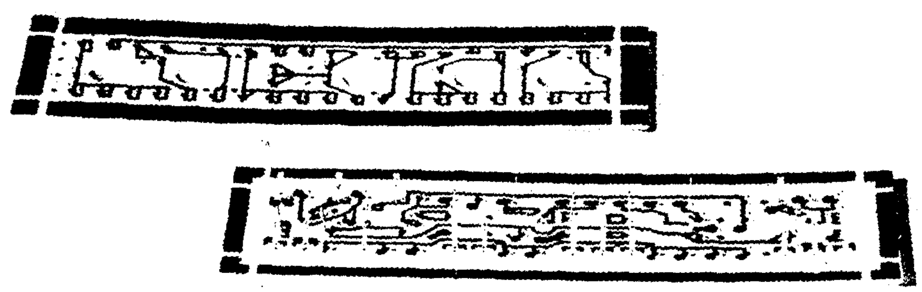


Fig. 4. These boards are similar to the previous ones, except that a wide band of nickel has been left around the outside. Holes could be provided for jigging if desired.

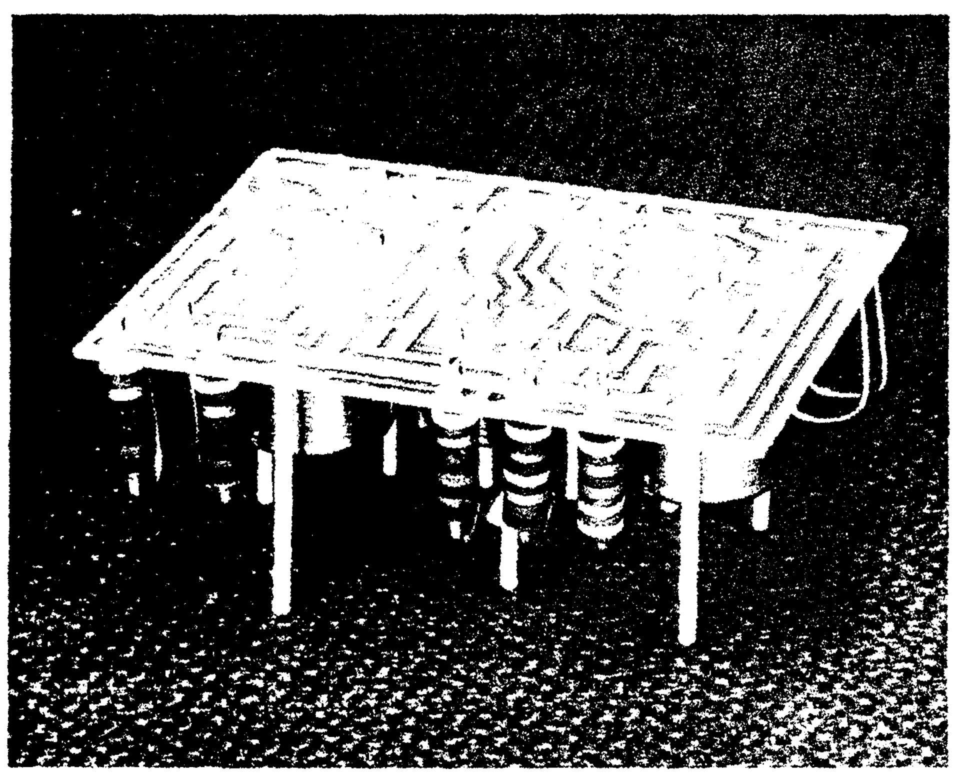


Fig. 5. This board shows fairly high wiring density but of greater interest is the fact that all the tabs are oriented in the same direction. When this is possible, it is less costly for us to lift tabs and less costly for the customer to weld them.

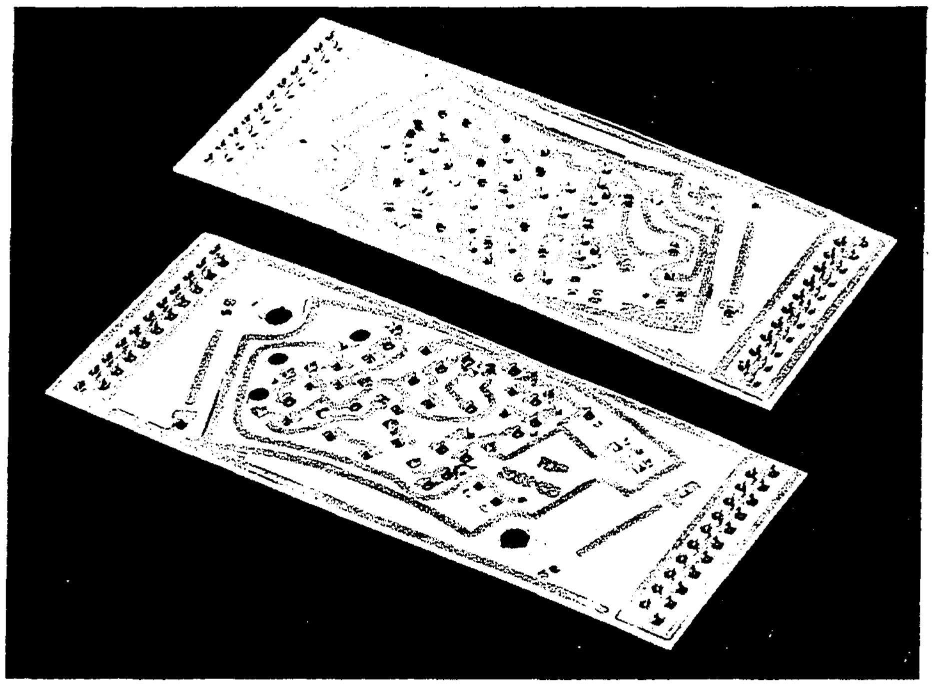


Fig. 6. Here is a pair of boards that demonstrates test tabs used for checking adhesion of the nickel to the board and more test tabs used for setting weld schedules. On the surface, these sound like good ideas, but when you consider that a large part of our cost is in lifting tabs, it may be a rather expensive way to make tests.

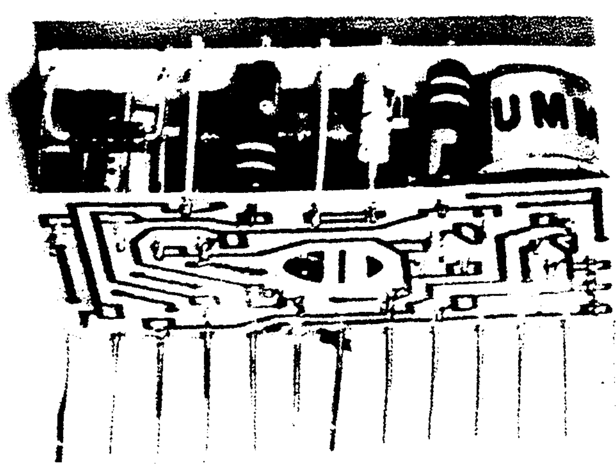


Fig. 7. This module uses leads welded to tabs for outside connections.

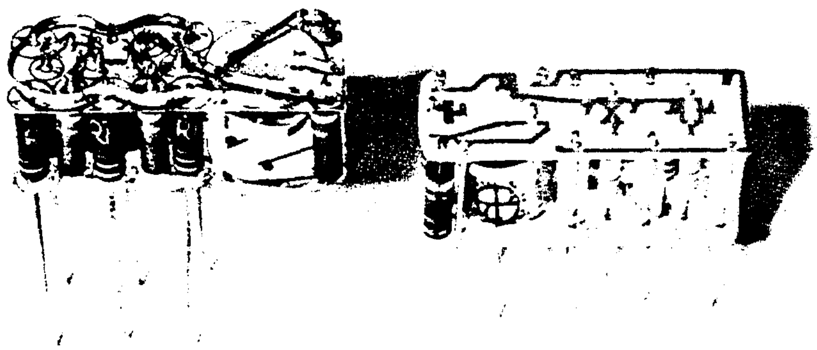


Fig. 8. The boards shown in this module were made for one of the packaging companies so that they could get a direct comparison of assembly cost between Intercon boards and point-to-point wiring.

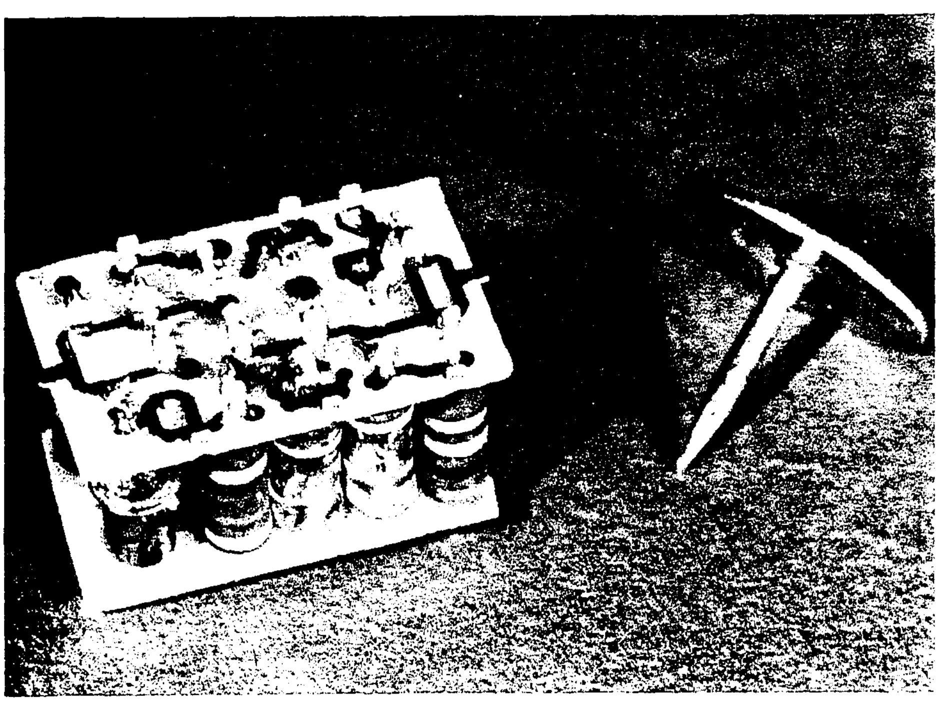


Fig. 9. This is a little flip-flop that we designed to demonstrate our technique. It is 0.56 × 0.345 × 0.33 in.

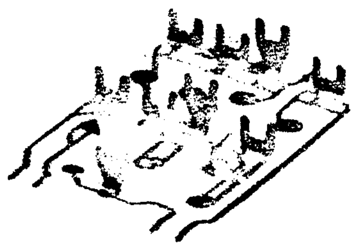


Fig. 10. While members of this symposium are probably not interested in soldering, I thought that you might be interested in seeing how the notched tab can be used.

Fig. 11. Here is the board shown in Fig. 10 with components soldered to the tabs.

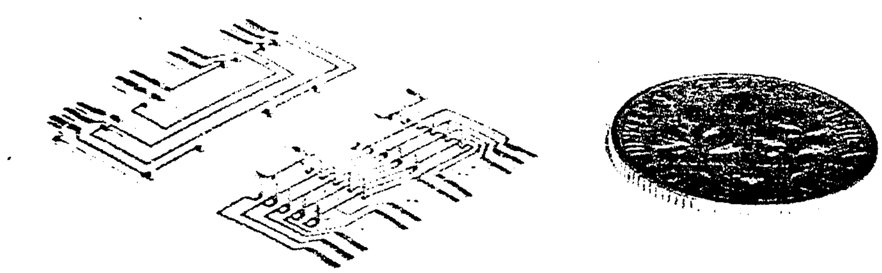


Fig. 12. Tabs can extend over the edge of boards as shown here. This board is used for interconnecting TI modules and their associated circuitry.

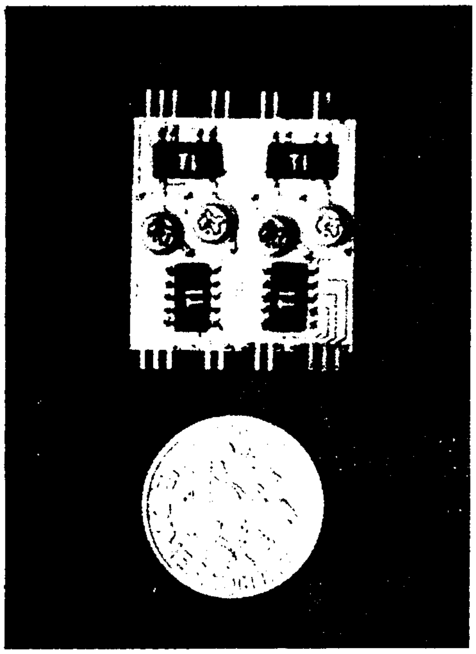


Fig. 13. Here is a completed assembly of boards similar to the one in the previous picture.

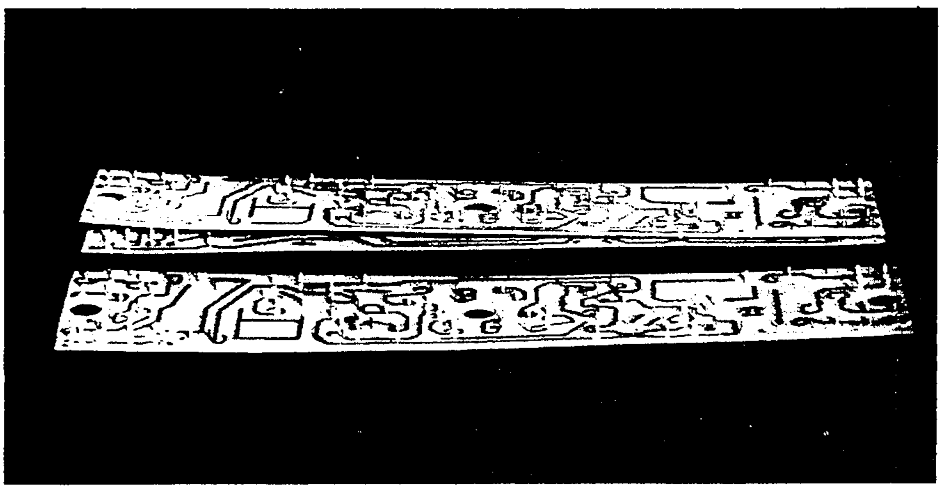


Fig. 14. The tabs provide a rather simple approach to multilayer systems. Tabs from the lower layer project past the top surface through clearance holes which also accommodate component leads. The accuracy of tab lifting is such that these boards go together easily.

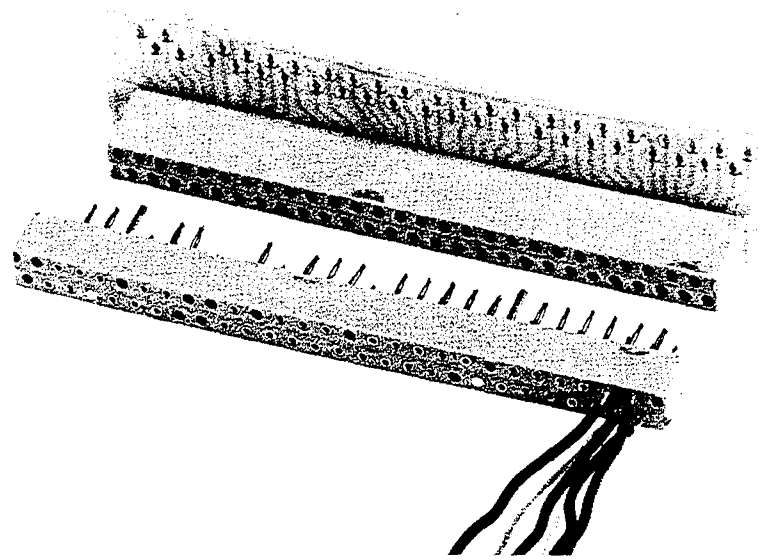


Fig. 15. Now we come to an entirely different concept though still using tabs. The circuitry is sandwiched between two layers of prepunched tape with tabs extending across the holes in the tape. These tabs are butt-welded to pins in the associated hardware, making a very compact assembly.

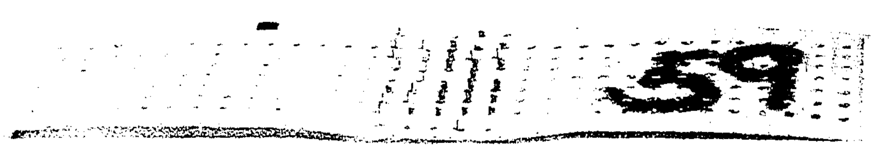


Fig. 16. Here is another flexible circuit designed to combine intercomponent connection and connector connection in one piece.

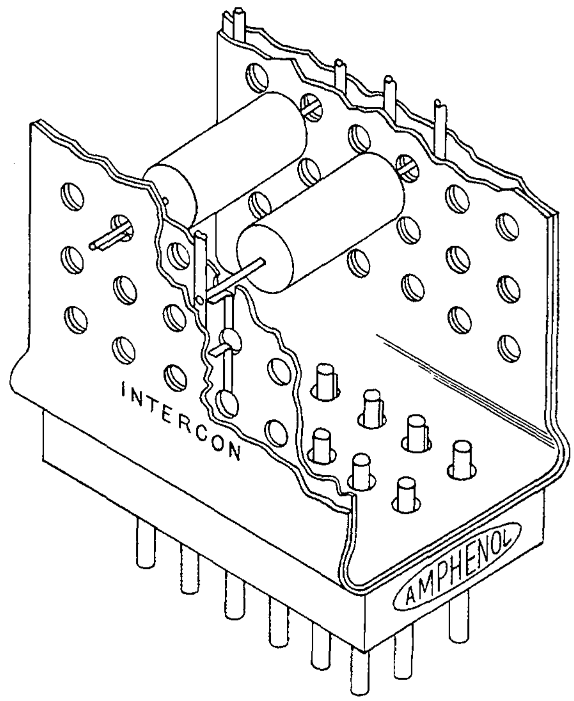


Fig. 17. This drawing shows how the piece shown in the previous picture is used. The tabs in the center of the circuit are welded to the connector pins. Then the wings are folded up and the components are welded to their respective tabs making a complete module.

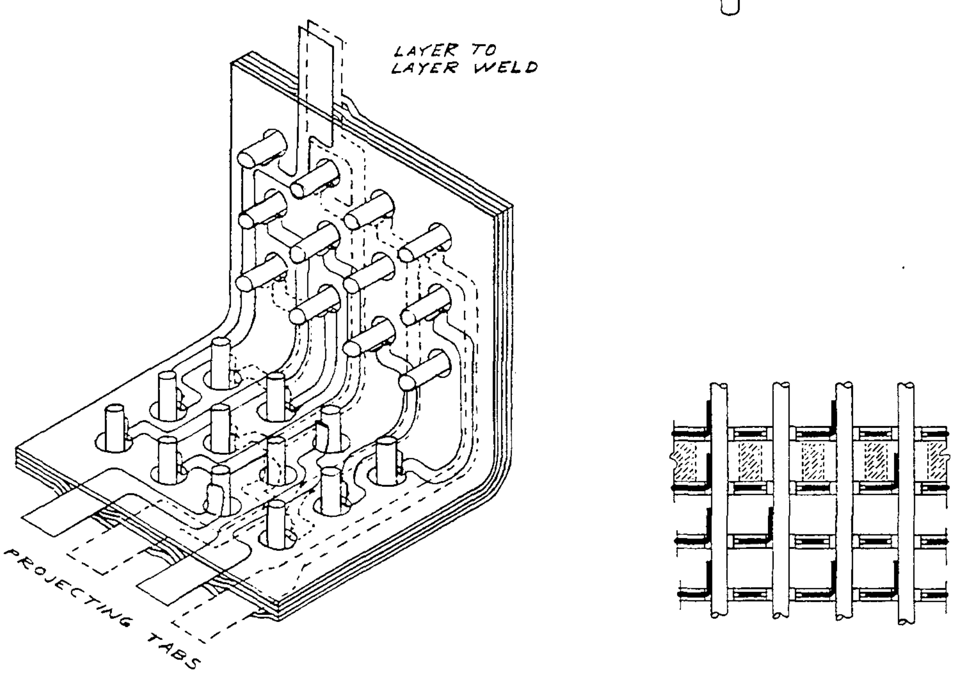


Fig. 18. This drawing shows another way of using multilayer circuitry. The top picture shows tabs extending over the edge either for interlayer connection or for outside connection. The lower picture shows how layers may be welded one at a time to form multilayer wiring.

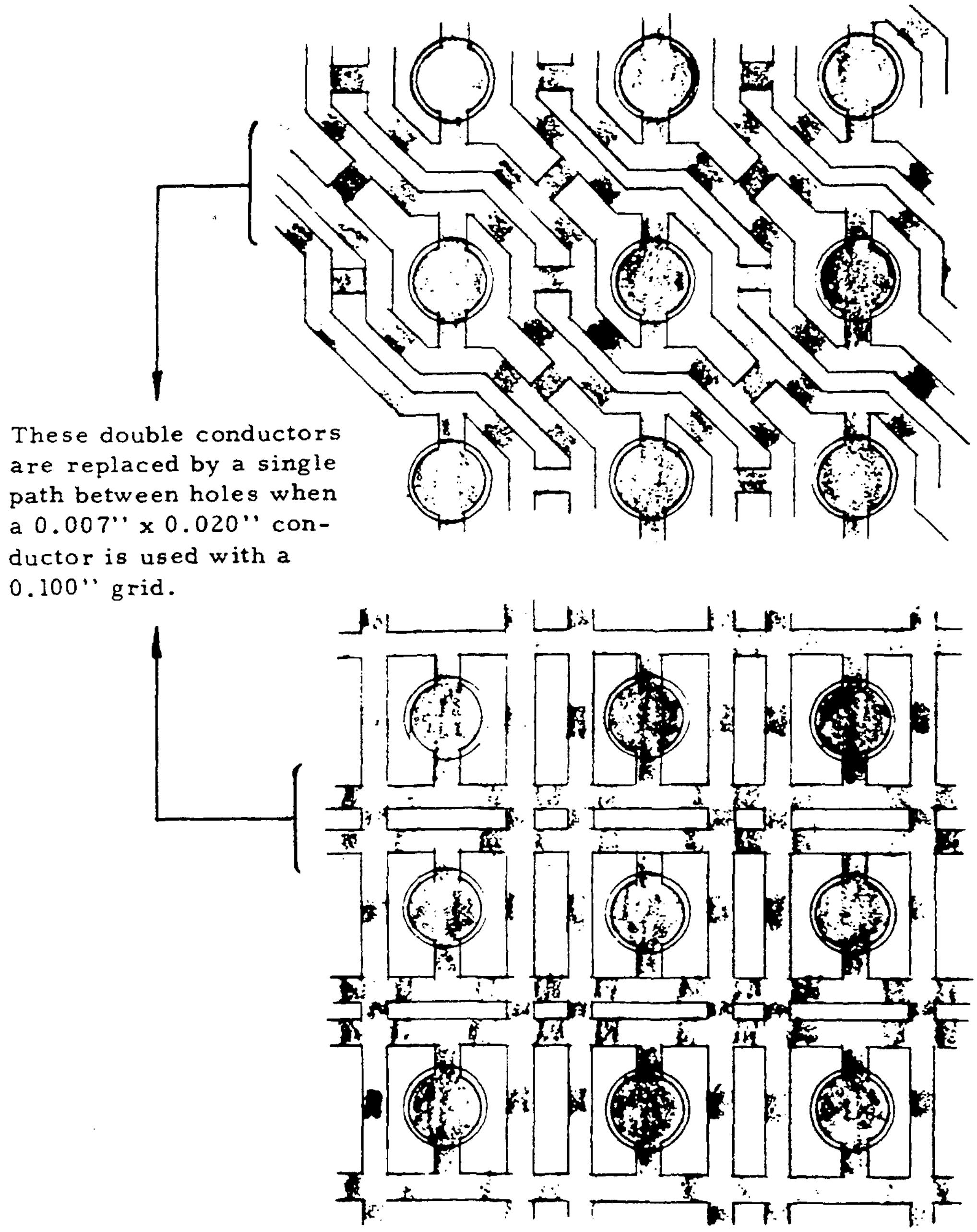


Fig. 19. Here are two ideas for generalized matrices. The idea in both of them is that unwanted conductors can be punched open.

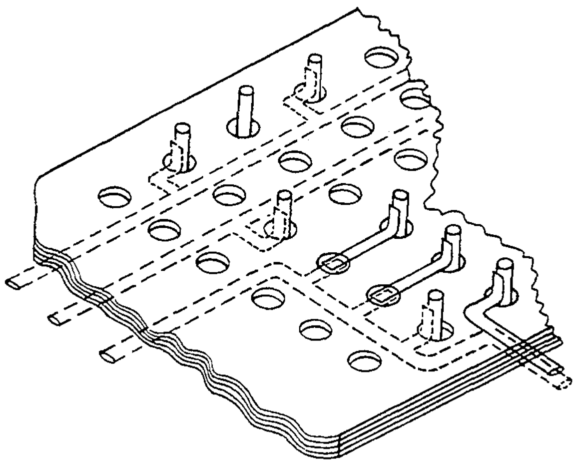
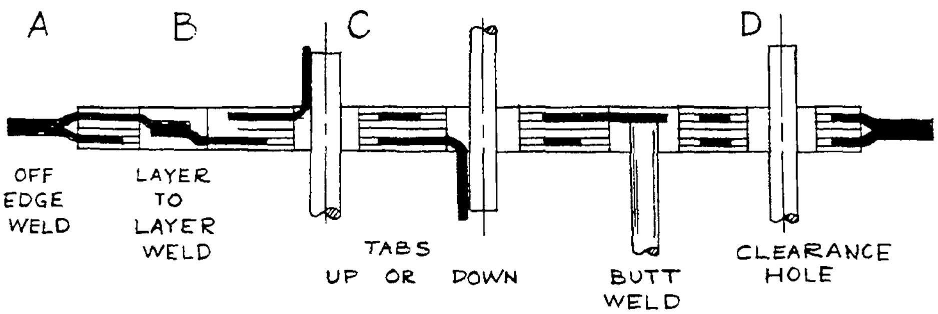


Fig. 20. This sketch shows the ways that a two-layer matrix system may be used.



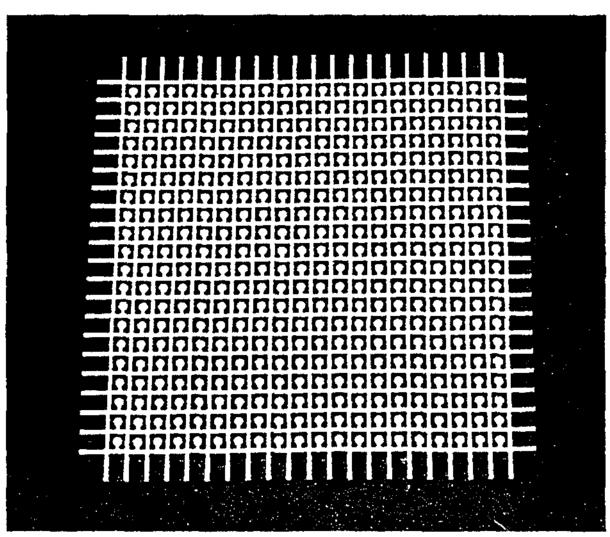


Fig. 21. Last but not least is this matrix. One can see that there is no insulation on either side of the metal; however, the intent is to supply these parts with punched tape on either side. Tools will be supplied to lift tabs where they are to be welded to leads, and to punch out unwanted conductors. It is apparent that unlifted tabs may be used for interlayer connection.

DISCUSSION

Q. (Paul Ehrlich, Fab-Tool, Inc., Englewood, Colo.) You made a statement about spacing of lines—etched circuitry *vs* deposited circuitry. Should your statement be qualified by stating that this spacing is more dependent upon techniques rather than processes?

A. I don't exactly know how to differentiate between techniques and processes because to me they are pretty much synonymous. The thing I was trying to say is that inasmuch as deposited circuitry is grown and in etched circuitry you have to remove material, theoretically you can put conductors closer together with deposit circuitry than you can by etching.

Q. (A. C. Gaetjens, General Electric Co., Valley Forge, Pa.) Have there been any Intercon circuits made of a size to accommodate the Texas Instrument solid circuits?

A. We have made some for two different customers and Texas Instruments came to us about four or five weeks ago saying they had a problem making circuits to accommodate their wafers and would we please help them. They came to us, designed their own circuits under our supervision and, I think, the circuits were shipped this week.

Q. (Jack A. Bingham, Bendix Systems Div., Ann Arbor, Mich.) Is it possible to make your boards in multilayer form?

A. It is possible, and in fact we made some for Bendix people in Teterboro. I wouldn't want to try it again right now, but we have made as many as five layers go together. We have made circuits for several people with three layers and in one of the most recent ones the company came to us with a six-layer system and we reduced that to three layers and sent it to them.

Q. (Jim Taylor, Neff Instruments, Duarte, Calif.) You spoke briefly about the ease of pushing these tabs up with the prototype grid. I wondered if you ever ran any test on vibration after these parts were mounted on the board.

A. I haven't run any test on vibration. I would hate to because the board is fairly flexible. It is primarily designed for people who want to make breadboards and if they want to encapsulate it, the rigidity of the board doesn't make any difference, but here is what it looks like. You couldn't expect it to stand any vibration.

Q. (Joe Ritter, Electronic Modules Corp., Timonium, Md.) I would like to know the approximate design cost for a typical flip-flop board—not the universal type but the special flip-flop you showed. Also, what is the approximate cost per board once it is designed in any quantity you would care to quote? You must have some kind of a bogey per hole or something.

A. Number one—we prefer people to make their own layout. If they do then the design cost is theirs, whatever they put into it. I say this advisedly because packaging engineers should be sitting pretty close to the circuit designer, if any changes are made then they can get it straightened out right there. If we are sitting half-way across the country from you, the designer, then any changes we make have to be approved by you, which takes time, telephone calls, and what have you. However, we do have a design staff of our own who will do this work and it will cost you about the same as if you lay out a circuit yourself. As far as the final cost of the board is concerned, it is hard to answer the question because I don't know the size of the board you are talking about. You make a sheet up, then you make as many lay-ups as you can on that sheet. This particular flip-flop probably has from a 100 to 150 per sheet up to the mechanical operation. Right now that would give an area charge of 10 to 20¢. The tabs at the present time cost approximately 4 ¢ apiece. Starting the first of the month, our new tape control tab lifter will be in operation and we expect the cost to go down to about $\frac{8}{10}$¢ per tab or less.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) What is the largest run you can make on the Intercon? What is the largest area?

A. The longest conductor you mean?

Q. What is the largest sheet you can get in Intercon?

A. Well, our plating tanks are 24 in. deep. I guess that is about as long as they could go with our present equipment. Actually, all of our production has been in smaller-size pieces. We have plating frames that will accommodate a 9 × 10 in. sheet of usable area. We are getting new plating frames that will give us 18-in. long sheets.

Q. (J. J. Bond, Fab-Tool, Englewood, Colo.) On what did you base the figure you quoted on the adhesion factor? Was it on the pull of the tab or with the bend of conductor?

A. It was on the pull of the tab. Nickel is probably one of the hardest materials to bond to. We searched a long, long time to get adhesives that would give us a decent bond. To give us a good pull strength we try to place anchoring area on the surface. This particular 1 lb is in a 50 × 100 thousandths area. Typical tabs run anywhere from a $1\frac{1}{2}$ lb to 3 or 4 lb.

Q. You stated that you could produce a finer line by deposition than by etching. Would you care to elaborate on the width of the line and the spacing that you can obtain?

A. I think one of the first jobs that we took was a requirement for a 3-mil line and a 3-mil space in a series of coils and we did it. That is the finest that we have done. There is no reason why you can't go finer, but the thing that has to be remembered is that plating grows sideways as well as up, so if you want thick metal you can't have narrow lines.

Q. (Leonard Schehr, Martin-Marietta, Baltimore, Md.) I noticed in the sample Intercon board that the circuitry seems to have a higher raised area in the center of the conductor. It didn't appear like a normal deposit circuit. I wonder if you could elaborate on that? Is that a special technique?

A. Can you see the blackboard? That is the photoline in your photo resist. If I start plating, I end up with a thing that looks like this because it grows sideways as well as up. This is a photoline about $\frac{8}{10}$ thick.

How Altitude Affects Forced Air Cooling Requirements of Electronic Equipment

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This paper deals with the effects of ambient air density on the weightflow of air delivered by an air moving device to a package requiring cooling, and shows the way in which this change in weightflow governs the component temperature rise above ambient temperature. A typical example indicating the use of the contained information is presented.

THE PROBLEM

In general, electronic equipment packages with forced air cooling are required to operate satisfactorily without overheating at some maximum altitude and ambient temperature, whether or not the equipment is intended for airborne use. Since the selection of the correct air moving device is intimately related to the maximum altitude and temperature of its application, it is important that the packaging engineer understand the effects of air density upon the capabilities of forced air cooling.

This paper will show how ambient air density affects the weightflow of air delivered by an air moving device to the package requiring cooling, and how this change in weightflow governs the component temperature rise above the ambient air temperature.

EFFECT OF AIR DENSITY ON COOLING AIR WEIGHTFLOW

Figure 1 shows the customary presentation of air moving device performance at constant air density. Also plotted on this performance curve is the system resistance curve of the equipment package, showing the pressure drop required to produce a given volume flow through the package. At the point of intersection of the fan performance curve and the system resistance curve, the pressure developed by the fan is equal to the pressure required by the equipment, and the flow which will be developed in the system is given by the value of the abscissa of this intersection. The weightflow is the product of the volume flow and the density of the air.

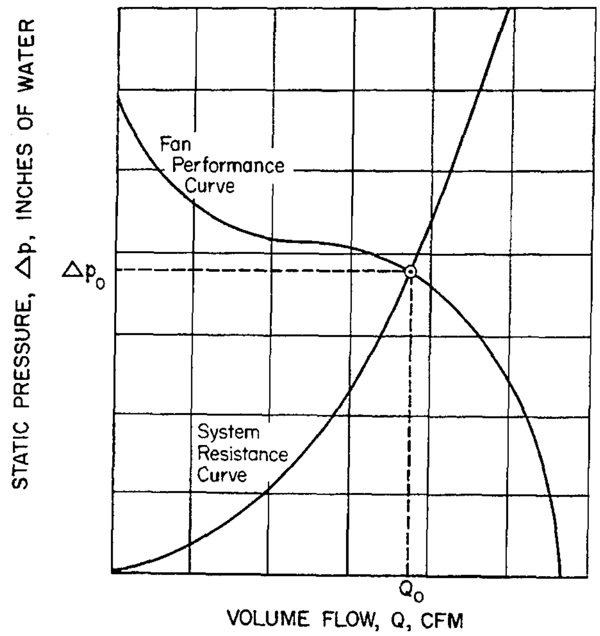

Fig. 1. Typical performance characteristics of an air moving device at constant density.

In general, the shape of the resistance curve shown on the coordinates of pressure drop *vs* volume flow at constant density is*

$$\Delta p = K_1 Q^n \tag{1}$$

where n has theoretical values of 1 for completely laminar flow and 2 for completely turbulent flow. While many system resistance curves are adequately described by a value of $n = 2$, many others are more accurately described by values of n in the range of 1.6 to 1.8.

For the case of a system for which $n = 2$, the calculation of the air weightflow delivered in air of density different from the standard density (for which Fig. 1 is appropriate) is straightforward and simple:

$$w_1 = \rho_1\left(\frac{N_1}{N_0}\right)Q_0 = \left(\frac{\rho_1}{\rho_0}\right)\left(\frac{N_1}{N_0}\right)w_0 \tag{2}$$

The subscript 1 refers to the new density condition, and the subscript 0 is used for the standard conditions; Q_0 is the volume flow at the intersection point in Fig. 1.

The speed N is included for generality, since a large number of fans employed for airborne electronic package cooling use highly load-sensitive motors, whose speeds vary over wide ranges with varying air density.

* A list of notation appears at the end of this chapter.

For the more general case, where $n \neq 2$, the exact weightflow delivered by a fan under conditions of varying density and speed can be determined only by graphical means, since the mathematical relationship of Eq. (2) is no longer valid.

The exact solution may be determined by plotting both system resistance and air moving device performance as $\sigma\Delta p$ *vs* w. When plotted to these coordinates, a single system resistance curve is obtained for all values of air density. See the Appendix for the derivation of this relationship.

The usual shape of a system resistance curve on coordinates of $\sigma\Delta p$ *vs* w is

$$\sigma\Delta p = K_2 w^n \tag{3}$$

where n is the same as in Eq. (1).

However, it should be noted that in the derivation of the $\sigma\Delta p$ *vs* w relationship for the system resistance in the Appendix, the form of the pressure drop relationship is not important to the validity of the results. If measurements show that the resistance curve is not represented by an equation of the form of Eq. (3), the $\sigma\Delta p$ *vs* w curve obtained by actual measurement will nonetheless be valid for different densities.

As shown in the Appendix, the performance curves for the air moving device take the shape of a family of curves for different values of σ, the shape of each curve depending upon the manner in which the fan speed varies with air density (motor loading).

As in the case of the performance curve and system resistance curve of Fig. 1, the flow developed through the system by the fan at any value of density ratio is the intersection of the performance curve for that density ratio and the resistance curve, for which the values of $\sigma\Delta p$ and w are necessarily identical.

Figure 2 is the performance of a small centrifugal blower whose speed varies over a range of 3:1 for a density change of 10:1, plotted to the coordinates of $\sigma\Delta p$ *vs* w. In general, the packaging engineer must rely upon the manufacturer of the air moving device to supply a plot of this type, since the testing required to make the calculations requires the use of airflow measuring equipment and altitude chambers not usually available to the user of air cooling devices.

To illustrate the effect that variation in the value of n can have on the weightflow delivered at high altitude, two system resistance curves are drawn in Fig. 2, each having the same coordinates at sea level ($\sigma = 1$), but one curve drawn for $n = 2$ and the other for $n = 1.6$.

At a value of $\sigma = 0.10$ (corresponding to an altitude of approximately 50,000 ft) the fan will deliver 0.47 lb/min into the system for which $n = 2$ and 0.33 lb/min into the system for which $n = 1.6$.

The point brought out by this example is that the exact shape of the system resistance curve has an important bearing on the amount of air delivered at very high altitudes. The higher the altitude, the greater the difference will be between the weightflow obtained in a system for which $n < 2$ and the weightflow calculated on the assumption that $n = 2$.

Physically, what is illustrated by the curves of Fig. 2 is the role of viscosity

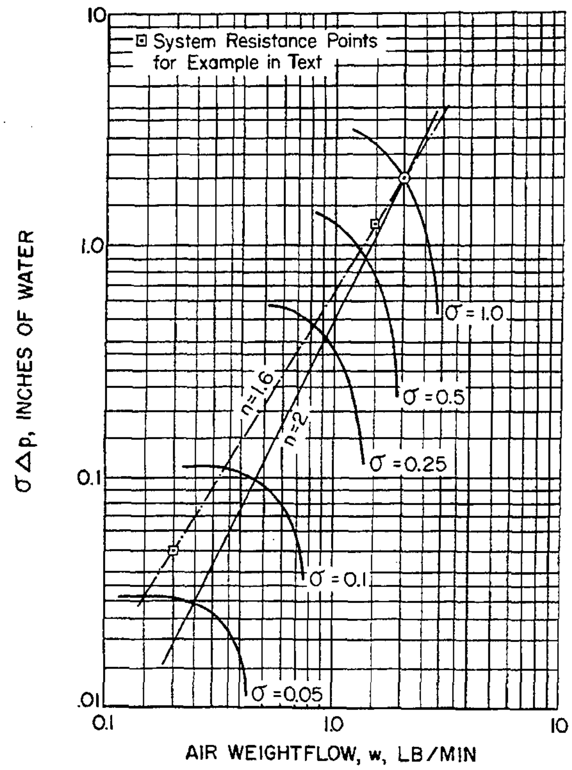

Fig. 2. Typical air moving device performance as a function of density ratio σ.

in determining the amount of air delivered to an equipment by an air moving device. The air moving device develops a pressure rise as a result of the dynamic effects of increasing the kinetic energy of the air passing through it. Therefore, its performance is influenced a negligible amount by viscosity. On the other hand, the pressure drop through the equipment package may be significantly influenced by viscosity. Since viscosity produces pressure drop only where there is a change in velocity from one fluid layer to the next, viscosity influences become important only in flow passages where there are large wall areas, at which the fluid velocity is zero, and relatively small cross-sectional areas through which the air must move. These conditions lead to high shear rates and, hence, to large components of viscous friction in the total package pressure drop.

The greater the proportion of the total system pressure drop represented by viscosity, the lower will be the value of the exponent n in Eq. (3). While a value of $n = 2$ will generally apply accurately to systems whose airflow passages consist of a series of contractions and expansions and turns, values of $n < 2$ will be found for equipments in which a large portion of the total system resistance consists of elements designed to promote heat transfer by use of extended surfaces, such as an anode cooler on a transmitting tube, for instance.

EFFECT OF COOLING AIR WEIGHTFLOW ON COMPONENT HEAT TRANSFER CAPABILITIES

The introduction of ambient air into a package for the purpose of lowering the temperature of its components achieves the desired result as a consequence of two effects:

1. The heat transfer coefficient of the relatively stagnant air film surrounding the components is increased.
2. The temperature of the air stream in the vicinity of the components is decreased.

These effects may be combined to relate the overall thermal resistance r, of a component to its geometry, heat transfer coefficient, and to the weightflow of cooling air by the following equation, which is derived in the Appendix:

$$r = \frac{T_c - T_1}{q} = \frac{1}{wC_p(1 - e^{-hA/wC_p})} \qquad (4)$$

The heat transfer coefficient h can be shown empirically to be related to the air weightflow over a fairly large range of weightflow by an equation of the form

$$h = K_3 w^a \qquad (5)$$

where K_3 and a are constants depending upon the component geometry. The value of a will be found to range from about 0.3 to 0.8, with a value of 0.5 being a representative figure for a typical electronic component. As with the exponent n of Eq. (3), the value of the exponent a increases with increasing turbulence.

Equation (5) may be combined with Eq. (4) to relate the component's thermal resistance to its geometry and the cooling air weightflow by eliminating h as follows:

$$r = \frac{T_c - T_1}{q} = \frac{1}{wC_p(1 - e^{-K_4/w_{(1-a)}})} \qquad (6)$$

where $K_4 = K_3 A/C_p$ is a constant for a given component configuration.

Figure 3 is a plot of Eq. (6) for a value of $a = 0.5$, and for various assumed constant values of K_4. Since it is the physical shape of the component which remains fixed while the weightflow of cooling air and the component thermal resistance vary, the validity of the assumptions underlying Eq. (6) may be verified by plotting experimental results on Fig. 3, and noting the closeness with which the resulting curve follows a line of constant geometry (K_4 = constant).

On Fig. 3 are plotted curves calculated from tube manufacturer's published ratings for small transmitting tubes likely to be found in airborne equipment. From these curves it can be seen that the assumption of a value of $a = 0.5$ bears a fairly close relationship to the facts.

Also plotted on Fig. 3 are lines of constant *utilization*, where the utilization η is defined as

$$\eta = \frac{T_0 - T_1}{T_c - T_1} = (1 - e^{-K_4/w_{(1-a)}}) \qquad (7)$$

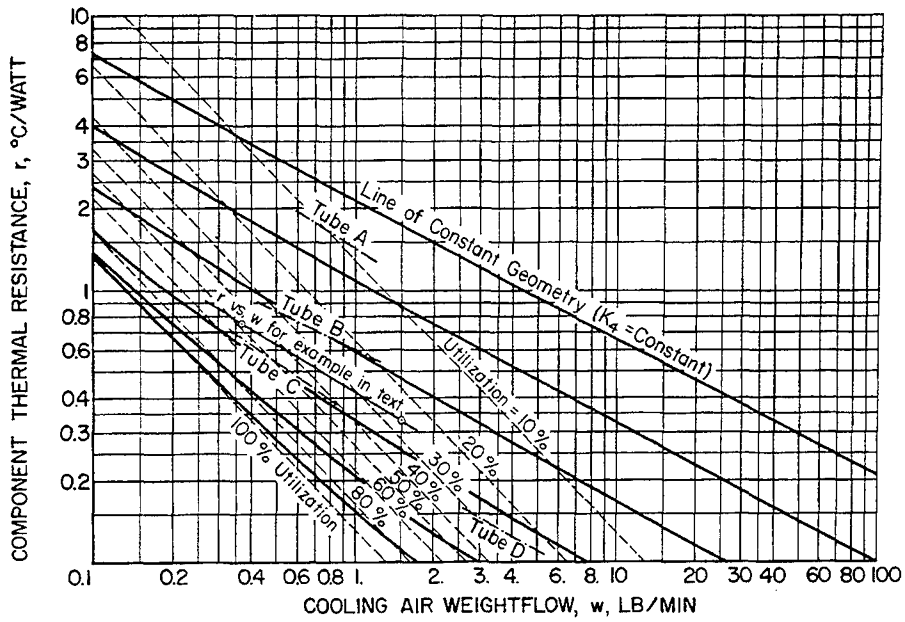

Fig. 3. Component thermal resistance as function of cooling air weightflow. Based on Eq. (6) for $a = 0.5$.

The practical significance of the utilization is that it is a measure of the closeness with which the temperature T_0 of the air leaving the component approaches the component surface temperature T_c. If the component had a very large surface with which to transfer heat, it might be expected that T_0 could be made to approach T_c, and the utilization would be quite high. On the other hand, where component heat transfer surfaces are small and air weightflows are high so that the outlet temperature does not rise much above the inlet temperature, the utilization will be quite low.

At very low utilization, the slope of the curve of r *vs* w on log–log coordinates can be shown to have a limiting value of $(a - 1)$. At the opposite extreme, a utilization of 1.0, the slope reaches a limiting value of -1.

EXAMPLE OF THE USE OF THE INFORMATION IN THIS PAPER

Given

A component continuously dissipating 300 w operates at a surface temperature of 170°C, when 1.5 lb/min of air at a temperature of 71°C are passed over it at sea level (barometric pressure—29.92 in. Hg). At these conditions, a pressure drop of 1.5 in. wg is required to move the air. When the airflow is 0.2 lb/min at these conditions of temperature and barometric pressure, the measured pressure drop is 0.06 in. wg. Maximum operating altitude is 50,000 ft. Temperature at 50,000 ft is 35°C per MIL-E-5400E Class 2 (see Fig. 5).

To Be Determined

The maximum component temperature must not exceed 250°C under any conditions of operation. The question is will the fan whose performance is shown in Fig. 2 provide adequate cooling?

Solution

From the pressure drop figures given, we may calculate the system resistance as follows: at 29.92 in. Hg and 71°C, the density ratio σ is

$$\sigma = \frac{9.65 \times 29.92}{(273 + 71)} = 0.84$$

Therefore, at $w = 1.5$ lb/min,

$$\sigma\Delta p = 0.84 \times 1.5 \text{ in. wg} = 1.26 \text{ in. wg}$$

and at $w = 0.2$ lb/min,

$$\sigma\Delta p = 0.84 \times 0.06 \text{ in. wg} = 0.05 \text{ in. wg}$$

Plotting these points on Fig. 2, we find they correspond to the resistance curve labeled $n = 1.6$.

At 50,000 ft the barometric pressure is 3.44 in. Hg (see Fig. 6). At 35°C, the density ratio σ is

$$\sigma = \frac{9.65 \times 3.44}{(273 + 35)} = 0.108$$

Figure 4 is a plot of weightflow *vs* density ratio for the fan and systems shown in Fig. 2. For the system labeled $n = 1.6$, the weightflow delivered by the fan is 0.37 lb/min at $\sigma = 0.108$.

From Fig. 3, the overall thermal resistance r may be found to be 0.76°C/w at

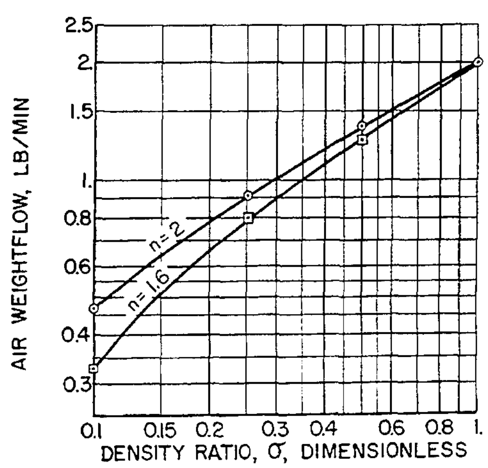

Fig. 4. Variation of cooling air weightflow with density ratio for example in text.

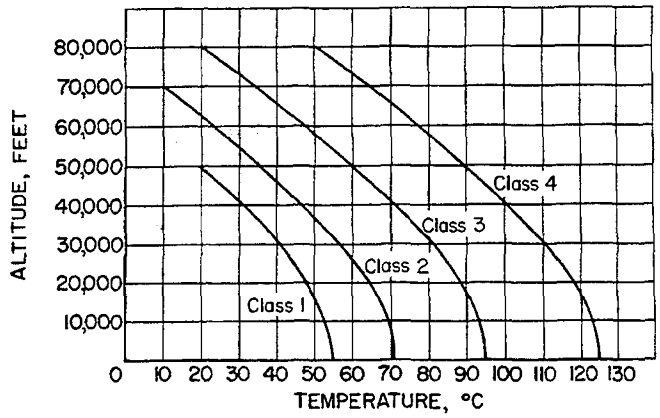

Fig. 5. MIL-E-5400E (ASG)—Requirements for continuous operation of airborne electronic equipment: temperature *vs* altitude.

$w = 0.37$ lb/min by drawing a line through the known sea level point of $r = (170 - 71)/300 = 0.33$°C/w at $w = 1.5$ lb/min, and parallel to the closest line of constant geometry. This construction assumes that the value of a in Eqs. (5) and (6) is 0.5. While this construction is satisfactory for estimating thermal resistance for unknown conditions, greater accuracy will be obtained if the actual values of a, or of r *vs* w, are known from test data.

The value of T_c may be calculated as follows:

$$r = \frac{T_c - T_1}{q} = 0.76\text{°C/w}$$

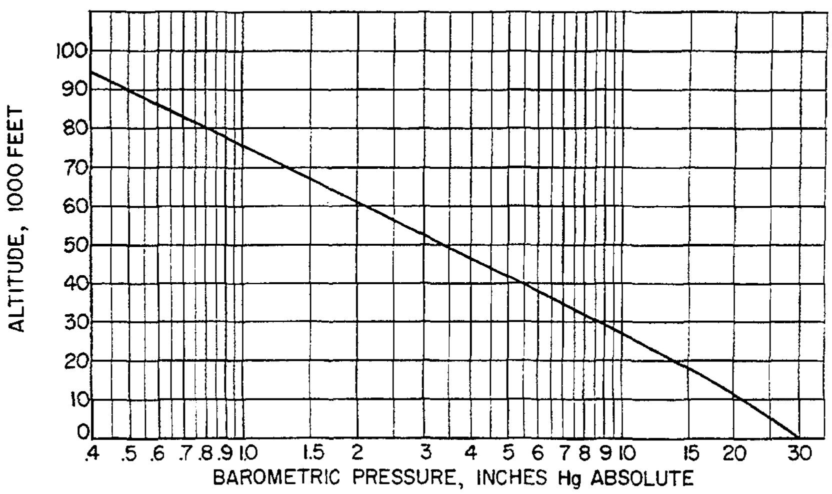

Fig. 6. ICAO standard atmosphere—barometric pressure *vs* altitude.

$$T_c - T_1 = 0.76q = 0.76 \times 300 = 228°\text{C}$$
$$T_c = 228 + T_1 = 228 + 35 = 263°\text{C}$$

which is greater than allowable.

If the airflow resistance curve had the same sea level ($\sigma = 1$) coordinates as the one used in the above example, but with a value of $n = 2$, we would have obtained a value of $w = 0.5$ lb/min at $\sigma = 0.108$ (see Fig. 4). For $w = 0.5$ lb/min, $r = 0.63$°C/w, and T_c would be 224°C, which is within the maximum allowable 250°C.

This example illustrates the necessity for a complete knowledge of system resistance characteristics prior to selection of an air moving device for cooling electronic equipment to be used at high altitudes. If it had been assumed, on the basis of a single measurement of system resistance at sea level, that the commonly used value of $n = 2$ was appropriate for Eq. (1), calculations would have indicated a safe margin of cooling capacity, whereas proof tests would have shown maximum safe temperatures to be exceeded.

In the case of this example, the ability of the blower to handle the required component temperature limitations is so close that the answer to the problem probably does not lie in selecting a larger blower, but rather in redesigning airflow passages to reduce airflow resistance, or in providing better heat transfer conditions around the component in order to utilize the airflow more effectively.

SAMPLE SPECIFICATION FOR AN AIR MOVING DEVICE FOR EQUIPMENT COOLING

Many times, manufacturers of air moving devices find themselves hampered in supplying the correct item to meet a customer's requirements because the specifications for the desired performance are either inadequate or misleading. The following sample performance specification should be followed to provide the minimum amount of information required to make the correct selection of an air moving device for use under conditions of varying density. (The numbers given in the table are intended as illustrative examples.)

Performance—The air moving device shall be capable of providing the airflows given in Table I when delivering air into the system whose resistance to air flow is specified in Table II.

It is important to note that it is necessary to specify the density of the ambient air corresponding to the given weightflow and pressure drop in Table II. This density need not be the same for all points, just as long as it is known. In the case of Table I, it is desirable to specify altitude and ambient temperature, rather than density alone, since the manufacturer of air moving devices must also evaluate the effects of this ambient temperature on the materials in his product.

The more points of specification given in Tables I and II, the more accurate will be the selection based on these data. In lieu of Table II, the system resistance may be specified as a curve of static pressure *vs* weightflow at a given density, or as $\sigma\Delta p$ *vs* w.

TABLE I

Airflow Requirements

	Air weightflow, lb/min	Altitude, ft	Temperature, °C
1.	9.7	0	71
2.	9.0	15,000	67
3.	7.8	30,000	57
4.	6.3	45,000	41

SUMMARY

The analyses of air moving device performance and component heat transfer characteristics given in this paper are intended to provide the packaging engineer with information which will permit the most accurate evaluation of the requirements for an air moving device to provide proper cooling. Although based upon a simple model, the heat transfer analysis gives results that correlate well with measured data.

By following the methods outlined in this paper, and by careful specification of the desired performance of the air moving device, the packaging engineer should be able to avoid the painful problems that arise from inadequate cooling of equipment.

APPENDIX

Derivation of $\sigma\Delta p$ vs w Relationship

System Resistance. The relationship of pressure drop to fluid velocity and fluid properties is stated in many standard texts on fluid mechanics, and is found by dimensional analysis to be

$$\Delta p/\rho V^2 = f_1[(\rho VD/\mu), \text{(geometry)}] \tag{8}$$

where f_1 indicates a functional relationship to be found by experiment. The term

TABLE II

System Resistance Characteristics

	Static pressure drop, in. wg	Air weightflow, lb/min	Air density, lb/ft³
1.	1.53	15.0	0.075
2.	1.45	10.0	0.038
3.	1.21	6.0	0.019
4.	1.45	3.0	0.010

(geometry) indicates that the same functional relationship will hold for all geometrically similar flow paths. The term $(\rho VD/\mu)$ is the familiar Reynolds number, which is a measure of the ratio of inertia forces to viscous forces.

For a fixed flow path, the geometry is invariant, and therefore it and the characteristic dimension D may be eliminated from the functional relationship, which may be rewritten

$$\Delta p/\rho V^2 = f_2[\rho V/\mu]$$

since $\rho V = w/S$, where S is the cross-sectional area of the flow path at which the velocity V is measured,

$$\Delta p/\rho V^2 = \rho \Delta p/(w/S)^2 = f_2[w/\mu S]$$

Introducing density ratio, $\sigma = \rho/\rho_0$, we obtain

$$\sigma \Delta p = \frac{w^2}{S^2 \rho_0} f_2[w/\mu S]$$

Since the cross-sectional area S is fixed for a given flow path, and since the viscosity of air μ varies only slightly over the ranges of temperature and barometric pressures involved in forced air cooling, these items may be eliminated and the functional relationship may be rewritten as

$$\sigma \Delta p = \frac{w^2}{S^2 \rho_0} f_3[w] \tag{9}$$

It will be seen from Eq. (9) that $\sigma \Delta p$ is a function of the weightflow w alone, so that, for a fixed flow path, a single curve will result for all normal variations of density, if a system resistance curve is plotted as $\sigma \Delta p$ *vs* w.

Air Moving Device. By the methods of dimensional analysis, which are given in numerous texts, the following functional relationship is found for the performance of an air moving device over a large range of change of variables:

$$\Delta p/\rho N^2 D^2 = f[Q/ND^3] \tag{10}$$

As in the section immediately above, σ may be introduced to yield

$$\sigma \Delta p = N^2 D^2 \sigma^2 \rho_0 f[w/\sigma \rho_0 N D^3] \tag{11}$$

Since the speed is determined by the motor-blower characteristics and the density, and since the diameter D is constant for the air moving device under consideration, the value of $\sigma \Delta p$ for the air moving device is determined by w, if σ is held constant. Therefore, a curve of $\sigma \Delta p$ *vs* w will result for each value of σ held during test.

Derivation of Eq. (4)

For a component with a uniform surface temperature T_c, dissipating q watts through the surface area A, the differential rate of heat transfer to the air passing by the surface is

$$dq = hdA(T_c - T) \tag{12}$$

where h is the heat transfer coefficient and T is the bulk temperature of the cooling air.

In passing by the surface dA, the air absorbs heat at the rate dq, and rises in temperature by an amount dT. The heat transfer rate and temperature rise are related to the weightflow rate of the air by:

$$dq = wC_p dT \tag{13}$$

Combining (12) and (13),

$$wC_p dT = hdA(T_c - T)$$

$$\frac{dT}{(T_c - T)} = \frac{hdA}{wC_p}$$

and integrating, we obtain

$$\int_{T_1}^{T_0} \frac{dT}{T_c - T} = \int_0^A \frac{hdA}{wC_p}$$

$$-\ln\left(\frac{T_c - T_0}{T_c - T_1}\right) = \frac{hA}{wC_p}$$

$$T_c - T_0 = (T_c - T_1)e^{-hA/wC_p} = T_c e^{-hA/wC_p} - T_1 e^{-hA/wC_p}$$

$$T_c(1 - e^{-hA/wC_p}) = (T_0 - T_1) + T_1(1 - e^{-hA/wC_p})$$

Noting that $T_0 - T_1 = q/wC_p$, we see that

$$(T_c - T_1)(1 - e^{-hA/wC_p}) = T_0 - T_1 = \frac{q}{wC_p}$$

or

$$\frac{T_c - T_1}{q} = \frac{1}{wC_p(1 - e^{-hA/wC_p})} \tag{14}$$

which is the desired form of the equation, since it relates thermal resistance to air weightflow, component area, and heat transfer coefficient, all of which are factors related to component geometry and air moving device performance.

NOTATION

- A Component surface area through which heat is transferred, ft^2
- a An exponent, dimensionless
- C_p Specific heat of air, w-min/lb-°C
- e Base of natural logarithms equal to 2.7183
- h Heat transfer coefficient associated with area A, w/ft^2-°C
- K A constant, significance determined by subscript and text

N Rotational speed of air moving device, rpm
n An exponent, dimensionless
P Barometric pressure, in. Hg abs
Q Air volume rate of flow, ft^3/min (cfm)
r Overall component thermal resistance, defined in text, °C/w
T Temperature, °C
T_c Component surface temperature, °C
T_1 Ambient air temperature, °C
T_0 Air temperature leaving package, °C
w Air weightflow, lb/min
Δp Pressure change, either rise across a fan or drop across a system, in. wg (water gage)
η Thermal utilization, defined in text, dimensionless
ρ Air density, lb/ft^3
ρ_0 Standard ICAO density equal to 0.0765 lb/ft^3
σ Density ratio $= \rho/\rho_0 = 9.65P/(273 + T_1)$, dimensionless

DISCUSSION

Q. (Herbert Morgan, Sylvania Electronics, Mountain View, Calif.) I would like to hear a few words about how you measure the resistance of equipment that you want to put a fan into. I think that needs some more attention.

A. To measure the resistance of the equipment you have to have reasonably elaborate test equipment, depending upon the size of the equipment to be cooled. You need a means of measuring the flow. In our case we used standard ASME rounded nozzles to measure the flow and water manometers to measure the pressure drop. If flow is very small, sometimes you can use Fischer & Porter flowmeters. An alternative to this, and this is a problem that we have recognized in our business, is to send your equipment (if it is not too huge) out to us and we would be extremely glad to measure its pressure drop characteristics so that you can be sure of getting the right fan.

Q. (Juris Eksteins, Litton Systems, College Park, Md.) Are you considering weight and mass the same here?

A. Yes, but it is technically more correct to use the term mass. Wherever you see weight flow in the paper, substitute mass flow.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) Can you comment on the difference in the effect of one of these air moving devices, in terms of its altitude characteristics, when it is used either exhausting or in-blowing the air, in terms of the turbulence conditions caused at the fan inlet? Is this a significant item in terms of change of the system utilization or the characteristics of cooling?

A. At the outlet of the fan you generally have air moving at quite high velocity and it is turbulent. If you direct this turbulent air right at your hottest components, you will doubtless achieve the maximum in heat transfer. Also this velocity represents energy that the fan has put into the air which you might, by duct work, be able to utilize by restoring it to static pressure. When you put an air moving device on a discharge side of a piece of equipment, you are throwing kinetic energy away; you don't stand any chance of recovering it. However, by putting it on the outlet you achieve more uniform velocity through your equipment. In a card chassis, for instance, where you want uniform airflow, it is sometimes desirable to mount your air moving device on the exhaust end of the equipment.

Q. (Jay Block, Hughes Aircraft Co., Culver City, Calif.) With regard to all those constants involved in the derivations. By this I mean K_1, K_2, K_3, K_4, and all the various constants of the equipment you were presenting in graphical form, is it a requirement to determine these constants empirically, or is this a service that you will perform?

A. I have an example worked out in the text. That curve (Fig. 6) with the lines of constant geometry—the point of putting all of those on there is to save you the trouble of solving Eq. (6). I pointed out in the example in the paper that if you know your thermal resistance and mass flow at one point, then all you have to do is assume a value of $a = 0.5$ and you can draw a line parallel to a line of constant geometry and arrive at an altitude figure. Now 0.5 will suit some people, but if you like to use 0.3, or 0.8 you can work out the equations too and make your own graphs.

Q. (Gil Wittlin, Autonetics, Anaheim, Calif.) I would like to know if you can expand on how you determine values of n between laminar and turbulent flow? Is it based strictly on Reynolds numbers?

A. How you determine—you mean without measuring?

Q. Yes, without measuring. In other words, you use 1.6 and 2 in your presentation, and I was wondering how do you know it is 1.6, not 1.4?

A. You have to know by measurement. In the general case, if you took a piece of equipment that had, say, a filter and an anode cooler and numerous other components and then a discharge grill, it would defy description, I think, to work it out mathematically beforehand. You would just know as a guide that if you had very narrow passages and very large wall surfaces that you might be tending to get more and more laminar flow. In my judgment that 1.6 figure would represent a low side of what you could expect in practice. The value of n falls between 1.8 and pretty close to 2 for most equipments.

Q. Are there any curves for values other than the 1 and 2 and 1.6 that you showed?

A. Well, that is the value of the $\sigma\Delta p$ *vs* W relationship. You don't have to assume what the character of the flow is. You can measure it and plot it on that curve (Fig. 2) and arrive at the answers. I point this out in the text. Even if the curve on log–log paper has a break in it (transition from turbulent to laminar flow) the equation is still valid.

Space Seal Study*

ART SHAFRAN

Philco—a Subsidiary of Ford Motor Company, Western Development Laboratories, Palo Alto, California

This study was undertaken to evaluate present methods for sealing electronic packages intended for space environment for 1 year or more. Temperatures of −34° to 150°C and a typical package, 12 by 8 by 6 in., were used. Containers should be fabricated from wrought metals drawn to shape or machined from a solid wrought block. If joints are welded, the materials should be carefully selected to minimize porosity and the development of residual stresses. Welds should be stress-relieved after welding. Covers are best sealed by soft-soldering. Welding is next recommended. The elastomer *Gasko-Seal* is best for package maintainability but least reliable when compared with soldering or welding because of the difficulty in obtaining reliable leak data. Sealed connectors can be obtained with permissible leakage rates but should be leak-tested before package installation.

EFFECTS OF VACUUM ON ELECTRONIC EQUIPMENT

VACUUM FOUND IN space environment can affect the operation of electronic equipment in two important ways. First, in the absence of atmosphere, sublimation or evaporation will deplete the material of which electronic components are made, thereby changing their physical and electrical properties. When their properties change, components are likely to cause inadequate equipment operation or equipment failure. Second, friction between moving parts substantially increases in vacuum. Mechanisms requiring precise relative motion such as gears, cams, and bearings will not be able to perform reliably in vacuum.

In addition, electronic components can be affected by sublimation of materials surrounding them. It is possible for metallic molecules to leave their base material in the process of sublimation, and collect or plate within a complex of circuitry to form conduction paths. Cadmium and zinc commonly used for platings, when exposed to vacuum, will lose 0.040 in./year at respective temperatures of 122°C and 226°C[1]. This is almost certain to impair the operation of most electronic equipment.

Another interesting aspect of the effect of vacuum on materials is the removal of surface gas film. All materials have a layer of gas on their surfaces at sea level. The

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removal of this adsorbed layer will decrease the resistance to the flow of current. Contact resistance, for example, would decrease. Generally, this phenomenon is helpful except where a circuit is dependent upon a particular surface resistivity.

The undesirable effects of vacuum on electronic components can be eliminated by preserving atmosphere in the equipment container. Figure 1 shows two typical electronic packages, which were used for a Philco communications satellite. Both were sealed against space vacuum to eliminate the effects of friction in vacuum between moving parts.

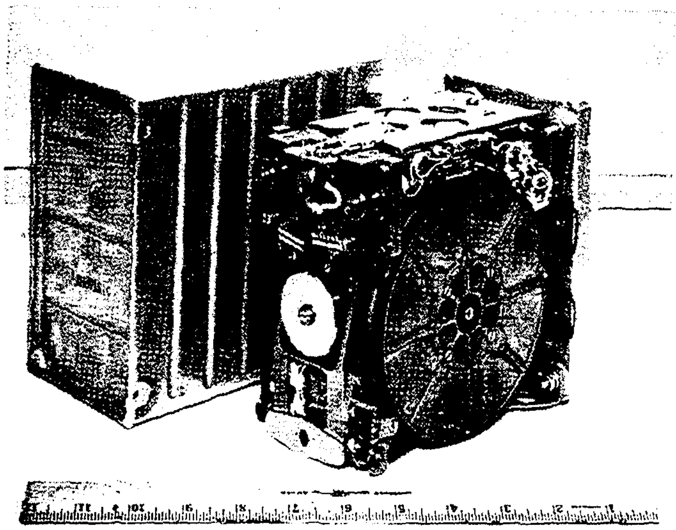
LEAKAGE RATE

Trying to maintain sea-level pressure in a container surrounded by vacuum introduces the problem of leakage. As air leaks from a space package, the pressure drops and over a period of a year or more, the package pressure could become low enough so as to cause equipment failure. If high electric potentials are utilized in the package, then internal pressure must be kept above the pressure at which arcing would be encouraged. Pressures required to prevent arcing will usually preclude material sublimation and other effects of hard vacuum. However, in cases where voltages are very low, e.g., in solid state devices, and when very thin films are used, the effects of vacuum on material may become the determining factor in establishing the low-pressure limit within the package.

When the minimum package pressure has been determined and the time established for package survival in space, an allowable leak rate can be computed. Leak rate is the volume of air at standard pressure and temperature issuing from the package per unit time. When package leak tests are performed—usually with a mass spectrometer leak detector—the results can be compared with the allowable leak rate value to determine whether the package will meet the design requirements. In addition, the allowable leak rate can be used to determine sealing methods and techniques for a particular package. A package expected to maintain an internal pressure above 200 mm Hg for 10 years in space would not be designed with the sealing methods that could be used for a container required to maintain the same pressure for 6 months.

Package leak rate will be directly proportional to the internal pressure during viscous flow. When package pressure becomes quite low and the flow is molecular, the leak rate can be assumed constant. Viscous flow occurs when the flow is limited by the frequency of collisions between molecules. When the flow is restricted by the collisions between molecules and the orifice walls, the flow is molecular[2]. The exact crossover point will vary with each package but it will usually occur at a pressure of less than 1 mm Hg[2]. For most electronic packages, the critical pressure—the pressure at which the spark potential is at a minimum—will usually be more than 1 mm Hg, so that viscous flow considerations could be used to determine permissible leak rate when designing a package which will fail due to a potential arc.

When the allowable pressure is in a region where the container air or gas will escape by viscous laminar flow, then from the gas laws, the pressure will vary with



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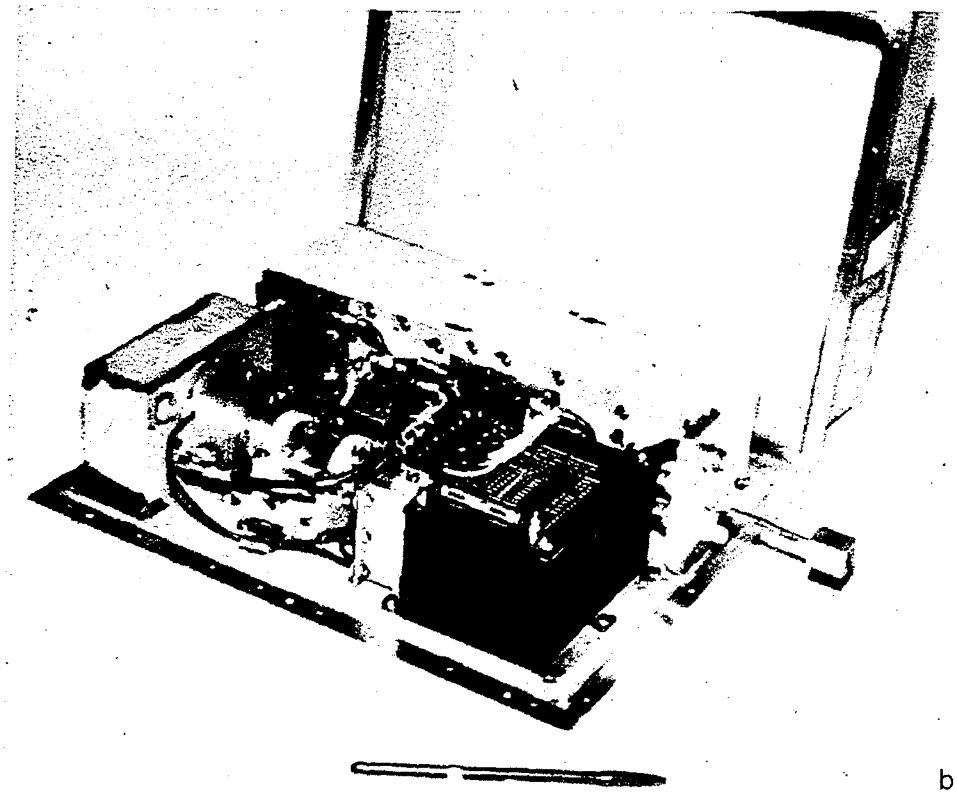

b

Fig. 1. Packages designed for space vacuum: (a) data storage unit; (b) microwave transmitter.

the volume leaving the container per unit time. This relationship can be stated as follows:

$$\frac{V - L_a t}{V} = \frac{P}{P_0}$$

where P is the instantaneous pressure (mm Hg), P_0 is the original pressure (mm Hg), L_a is the average leak rate (volume per unit time), t is time, V is the package volume (container volume less equipment volume), and

$$P = P_0\left(1 - \frac{L_a t}{V}\right)$$

or

$$L_a = \left(1 - \frac{P}{P_0}\right)\frac{V}{t} \qquad \text{for} \quad t > 0$$

From the above formula, an average leakage rate can be computed which is not the leak rate sought just prior to placing the package in space. Since leak rate is proportional to pressure, the required leak rate can be found by a simple relation:

$$L = \frac{P_0}{P_a}L_a$$

where L is the design leak rate and P_a is the average pressure difference.

As an example of how to find the permissible leak rate for viscous flow, assume that a container 12 by 8 by 6 in. is filled with electronic components to 80% of its volume. The time required to operate in space is 1 year and the pressure cannot fall below 200 mm Hg as determined by the potential in the container and its smallest gap[3]. The average leak rate will be

$$L_a = \left(1 - \frac{200}{760}\right)\frac{1890 \text{ cc}}{8760 \text{ hr}} = 0.158 \frac{\text{cc}}{\text{hr}}$$

and

$$L = \frac{760}{480}(0.158) = 0.250\frac{\text{cc}}{\text{hr}} = 0.695 \times 10^{-4} \frac{\text{cc}}{\text{sec}}$$

When working with pressures below 1 mm Hg, one can assume the leak rate is constant and the following equation can be used[2,4]:

$$P = P_0 e^{-(L/V)t}$$

and

$$L = (\ln P_0 - \ln P)\frac{V}{t}$$

CONTAINER FABRICATION AND MATERIALS

Leakage through metal container walls can occur from microscopic or molecular flow and from macroscopic flow due to porosity or cracks in the metal. Molecular flow through metals by most gases, including air, is evidenced at very high temperatures, approaching the metal's melting point, and at high pressures[5]. Space electronic package containers will probably be sealed with 1 or 2 atm and they will experience temperatures up to 150°C. Therefore, if leakage occurs through the metal, it will be through porosity or cracks and not through molecular separations.

Castings are a poor choice for sealed space containers. They are apt to solidify with porosity because of entrapped air and nonmetallic inclusions. With special mold design and handling, they can be made pore-free, but few foundries have this capability and it is costly.

Wrought metals are made from cast ingots subjected to hot-rolling operations. Hot-working eliminates porosity. However, when wrought metals are jointed by welding, they may develop porosity and cracks at the joints. Processes occurring during welding are essentially the same as those taking place in the melting and solidification of metals in normal foundry operations[6], so that porosity of weldments occurs in the same manner as in castings. Additionally, during welding residual stresses are caused in the weldment by expansion and contraction of the

TABLE I

Preferred Container Fabrication and Alloys for Sealed Space Containers

Fabrication and Alloy	U.S. Government Designation(s)	Comments
Machined Containers		
Aluminum 6061-TO Alloy	QQ-A-367	
Magnesium AZ31B-O Alloy	QQ-M-44	
Drawn Containers		
Aluminum 3003-O Alloy	QQ-A-359	
Magnesium AZ31B-O Alloy	QQ-M-44	
Welded Containers		Cracking tendencies increase as residual stress in a material increases. Thus, when welding, 6061-T6 is more susceptible to cracks than 6061-T4. 6061-TO is least susceptible to cracks but strength properties are lower. Welds must be stress-relieved.
Aluminum 6061-TO Alloy		
Welding Rod 6061-TO	QQ-A-327, QQ-A-367	
Magnesium AZ31B-O Alloy	QQ-M-44	Cracking tendencies increase with temper increase. Welds must be stress-relieved.
Welding Rod AZ92A-O		

weld and base metal. Unless special precautions are taken, such residual stresses are always present and they can result in cracking of the welds. This is particularly significant with magnesium alloys.

Residual stresses, resulting from welding, can be eliminated by properly stress-relieving the welded joint. However, stress-relieving heats may endanger electronic components within the container, so container packages should be designed to protect components if final sealing must be made by welding.

Although porosity and cracks in metal walls can be filled with impregnants, it was found at the Philco Western Development Laboratories that with temperature cycling the impregnant tends to break away from the metal and open a path for leakage. Another problem with impregnants is that in vacuum they sublimate and, in time, sealed pores and cracks can open. The sealing properties of a small amount of impregnant forced into a minute crack or pore could become appreciably weak when subjected to sublimation for a short period of time, although it is difficult to predict how long an impregnant will remain effective.

The best way to fabricate containers intended to seal electronic equipment in space is to use wrought material drawn to shape or machined from a solid wrought block. Although more expensive for small quantities, they provide the most reliable leaktight walls between vacuum and atmosphere over long periods. Welded containers, properly stress-relieved, are next preferred (see Table I).

COVER SEALS

When electronic equipment is mounted in a container, the final sealing of the enclosure is usually made with a cover. Cover seals have to keep leakage below an established safe rate for a specified time. Also a cover should be capable of being conveniently removed and replaced for repair of the contained equipment.

Elastomer Seals

Elastomers refer to polymeric materials which can be elastically deformed. Such materials as natural rubber, butyl rubber, neoprene, silicone rubber, and Viton are considered elastomers. As a gasket type of seal, an elastomer offers an excellent means for opening a sealed container without damaging the seal or the joint flanges. Reuse of the seal and relatively loose machining requirements for the flanges add to its advantages. The most unreliable aspect of elastomers is the difficulty in demonstrating their sealing ability in a vacuum environment over a long period.

It is suspected that an elastomer's sealing ability is related to its weight loss in vacuum. Hard vacuum causes elastomers to deteriorate and their plasticizers to volatilize, resulting in loss of elastic properties. As elastomers lose weight and elasticity, they permanently deform when distorted between two surfaces and cannot forcibly close the seal interface to leakage paths. When butyl rubber was exposed to vacuum, its weight loss increased as vacuum pressure decreased[7]. Exposed to 1×10^{-7} mm Hg, the butyl rubber lost 2% of its weight while at 2×10^{-8} mm Hg it lost 31%. Leak rate increased over 1000 times at the lower pressure.

TABLE II

Decomposition of Polymers in High Vacuum*

Polymer	Temperature for 10% weight loss per year in vacuum, °C
Nylon	26.8–171
Vinyl Chloride	87.7
Methyl methacrylate	104.3–199
Acrylonitrile	115.5
Isobutylene-isoprene (butyl rubber)	121
Styrene	132–216
Vinyl acetate	160
Cellulose	176.5
Ethylene terephthalate (mylar, dacron)	203
Styrene, cross-linked	226–254
Ethylene, low density	238–282
Propylene	244
Vinylidene fluoride-hexafluoropropene (Viton-A)	254
Chlorotrifluoroethylene-vinylidene fluoride	260
Vinylidene fluoride	266
Ethylene, high density	293
Trivinyl benzene	293
Tetrafluorethylene	332

* From [1].

A number of studies have been made by chemists interested in the kinetics of vacuum pyrolysis of high polymers[1]. This and similar work measured the rate of weight loss of small samples of pure well-defined polymers as a function of time and temperature in vacuums of 10^{-6} mm Hg. The data indicate that rates of decomposition in vacuum are often greatly accelerated by small amounts of impurities and addition agents, including polymerization catalysts. The particular formulation and curing procedure used may have important effects upon vacuum stability. In no case reported were tests made for times approaching 1 year. Table II shows the relative merit of elastomers in vacuum as a function of temperature and fixed weight loss. In general, the tests were run for less than 24 hr and extrapolated to 1 year. The pressure at which the tests were conducted was not reported.

In the section dealing with leakage rate, it was shown that a container 12 by 8 by 6 in., expected to survive 1 year, could permit an average leakage rate of 0.695×10^{-4} cc/sec or 0.174×10^{-5} cc/sec-in. of seal (assuming the seal length to be 40 in.). For the same package and a 10-year life, a gasket seal could permit a leakage rate of no more than 0.174×10^{-6} cc/sec-in. of seal (see Fig. 2).

Tests show[7] that a butyl rubber specimen used as a seal between two flanges will allow a leakage rate of 0.350×10^{-10} cc/sec-in. of seal at 2.2×10^{-7} mm Hg and 0.388×10^{-7} cc/sec-in. of seal at 2.2×10^{-8} mm Hg. By optimistically extrapolating these data (see Fig. 2), it can be seen that the leakage rate of a butyl rubber seal at 10^{-9} mm Hg would be 4×10^{-4} cc/sec-in. of seal. At this rate,

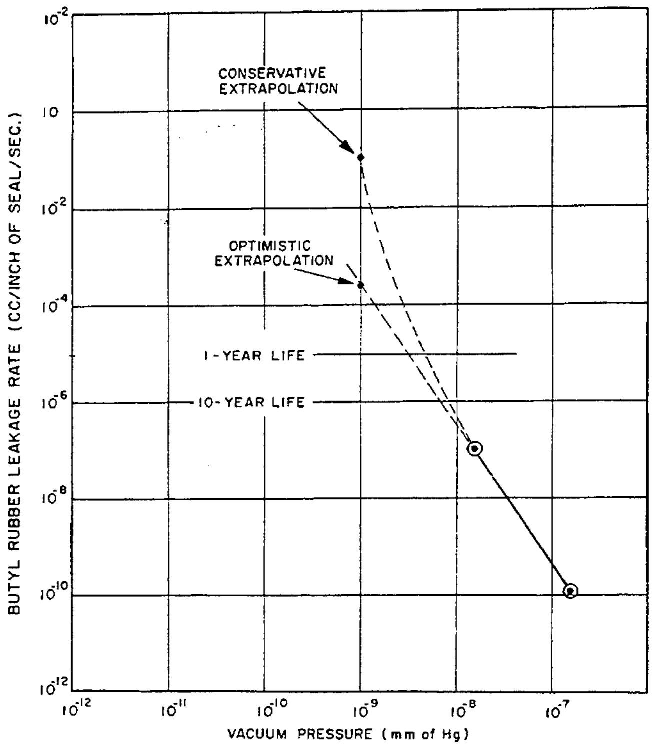

Fig. 2. Butyl rubber gasket seal leakage rate as a function of vacuum pressure.

package life would be about 1 day. Figure 2 also indicates the importance of making package-leak tests in vacuum. A package-leak test made at atmospheric conditions will usually show a smaller leak rate than when tested in vacuum.

Space vacuum pressures can reach 10^{-15} mm Hg and less. Though the pressure next to the elastomer seal may not reach as low a pressure as that outside the vehicle, because of outgassing and sublimation, the pressure may go to 10^{-9} or 10^{-10} mm Hg.

Leakage data for other elastomers, such as Viton or neoprene, used as seals in hard vacuum are not available. Until elastomer seals are thoroughly tested in vacuum for long periods of time, they should not be relied upon to safely seal electronic packages for 1 year or more.

When using elastomer seals in vacuum, it is important to consider leakage through the seal material or permeability. Table III shows that a seal made of silicon would allow a leak rate, due to permeability, approximately 10 times that considered minimum for the container leakage example given earlier. Although its stability in vacuum is better than most elastomers, its leak rate, due to permeability, is beyond that permissible in the type of electronic package of concern in this report.

Another aspect to consider when using a polymeric seal is the seal design.

TABLE III

Air Permeabilities of Elastomers[8]

Material	Permeability* × 10^{-7}
Butyl	0.32
Thiokol	0.37
Nitrile (High Acrilo Nitrile)	0.41
Nypalon S-2	0.70
Kel-F	0.80
Nitrile (Low Acrilo Nitrile)	0.80
Viton A	0.88
Polyurethane	0.97
Chloroprene	0.98
Acrylon EA-5	1.50
Hycar 4021	1.80
GR-S	2.90
Natural	4.40
Fluoro-Rubber IF4	9.60
Fluoro-Silicone	12.80
Silicone	45.00

* Permeability is expressed in cubic centimeters of air, corrected to STP, per second which would permeate through one square centimeter of vulcanizate one centimeter thick ($cc/sec/cm/cm^2$) at a temperature of 80°C.

Space sealing requires the seal to be exposed to a variation of pressure differentials. Changing distances from the earth can vary the external pressure several orders of magnitude and container leakage will change the internal pressure. Forces on the seal due to changes in the differential pressures tend to cause a slight movement of the seal which results in greater interface leakage. One way to prevent seal movement under changing pressure differentials is to mold the elastomer in a groove in one face of the container flange. Properly designed, the seal will almost completely fill the mold cavity when the container flanges are brought together and seal motion can be prevented when subjected to changes in pressure differentials. The Parker Seal Company markets a seal based on this principle called a *Gasko-Seal.* It can be supplied molded on both sides of a metal gasket or molded directly into the face of the container flange (see Fig. 3). An advantage of the separate metal gasket with the seal molded on both faces is that it can be replaced without discarding the container.

Elastomers recommended for short-time space sealing applications are butyl and Viton synthetic rubbers. Butyl is the least permeable material and it offers low radiation-deterioration characteristics. Viton, a fluoroelastomer, is among the most stable materials where heat resistance is required.

Metal Seals

Hard and soft metal seals are available today. A soft metal seal is designed to be permanently deformed by hard container flanges which deform elastically. A hard metal seal is designed to deform elasticity with the container flanges. The soft seal cannot be reused, while the hard seal can be used again. The main difficulty with soft metal seals is that they do not perform satisfactorily during

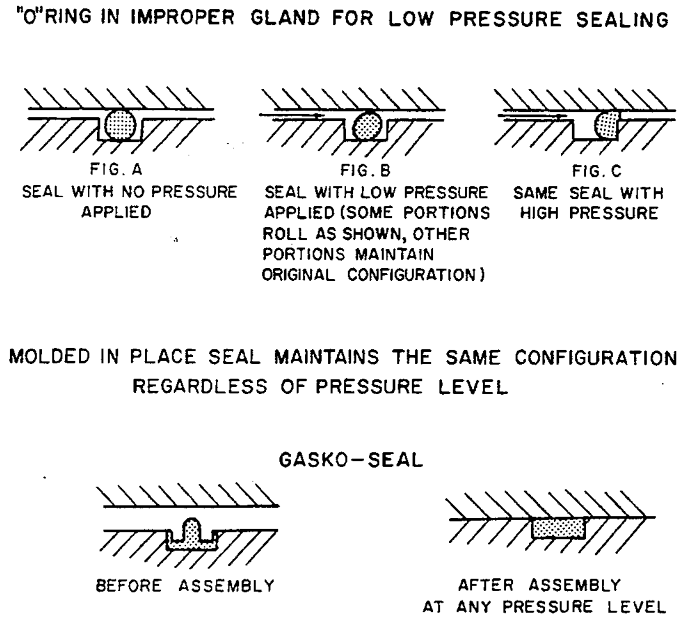

Fig. 3. O-ring compared with *Gasko-Seal.*

thermal cycling[9]. Soft metal seals are reliable within a temperature range of only a few degrees. With both types, hard flanges are required. Aluminum or magnesium flanges are too soft for use with metal seals.

In practice it has been found that metal seals can damage hard container flanges so that resealing may require remachining the flange seal surfaces. Also, to be able to evenly deflect the metal seal, the flanges must have a very fine surface finish and they must be parallel.

Fusion-Type Seals

It has been assumed that once a container has been welded closed and leak tests show no leakage that the seal will be maintained indefinitely. However, tests at the Philco Western Development Laboratories showed that leaks can develop in welded joints which have passed previous tests satisfactorily. It was concluded that welded joints develop stresses during welding, and in time can cause internal forces to crack the weld. Also, since a welded joint is similar to a casting as the molten metal solidifies at the joint, porous matrices can develop and with pressure cycling may open a leak path with time.

Part of the difficulty of a welded seal can be alleviated by properly stress-relieving a sealed joint after welding. However, in many cases this is not practical because of the possible damage to electronic components within the package when heat is applied during the stress-relieving process.

Impregnants have been used to fill pores in containers. However, with temperature and pressure cycling and exposure to vacuum, once-filled porous paths can open. Perhaps, in time, impregnant materials can be found which will seal porosities in metal for a space environment.

Soft-Solder Type of Seals

Soft solders secure attachments by virtue of a metal solvent or intermetallic solution operative at relatively low temperatures. The action of molten solder on a metal may be compared to the action of water on salt: the solder secures attachment by dissolving a small amount of the metal at temperatures much below its melting point[10].

For space-package sealing, soldering appears to be more reliable than welding. First, the lower temperatures needed for soldering (116°C for 50% In, 50% Sn) will not induce stresses. Second, solder, when properly applied, will not be porous. Third, a soldered cover can be more easily removed than a welded cover. However, a soldered joint must not be expected to support much load—especially in a shear condition—but this can usually be avoided by proper joint design. A fastening device should be used for holding the cover down and the solder should provide the seal. Figure 4 shows possible ways of sealing containers by welding and soldering.

Some work has been done at the Philco Western Development Laboratories to develop an induction heating method for soldering and unsoldering package covers. Localized heat can be applied by the induction loop to the solder seal and the cover can be lifted free of the package. Resealing can be accomplished by

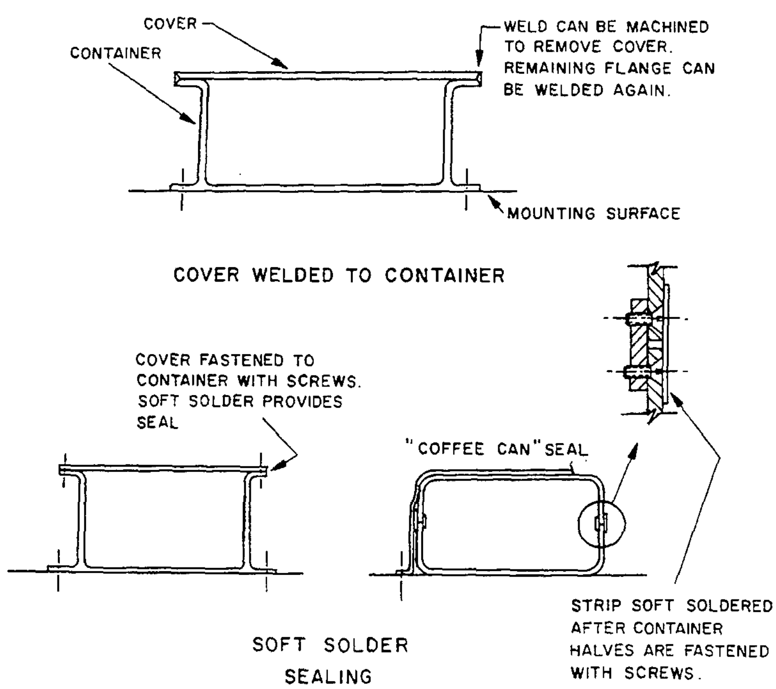

Fig. 4. Welded and solder seals.

forcing the cover onto the package while applying heat to a thin solder gasket. Heat damage to components will be minimized because of the short-time induction heat cycle.

ELECTRICAL CONNECTORS

The pressure in a space vehicle decreases during ascent. Electronic equipment connectors mounted to the outside of the container carrying voltages of over 100 v will have to be protected from arcing as the vehicle passes through the critical pressure. Critical pressure is that pressure at which the arc potential is a minimum. About the only way to protect against arcing is to fill the space between potential points with insulation material. This would make removal of equipment from a space vehicle difficult once installed for flight. The best solution is to design the equipment for voltage inputs and outputs of less than 100 v.

Sealed power connectors can be obtained having 2.1×10^{-6} cc/sec leakage or less at 30 psi differential. It is unlikely that each connector is tested by the manufacturer for leakage so that it is good practice to arrange for individual connector leakage tests. It is less costly to find a leaky connector before it is installed.

Flanges for an elastomer seal or solder can be provided. For space applications, solder is preferred for sealing between the connector and container (see the section on seals).

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DISCUSSION

Q. (Marvin Lubin, Pioneer Electric, Forest Park, Ill.) Does your discussion with respect to the elastomer seals apply also to plastic adhesives, epoxies seals, and that sort of thing? Do you have any comment on them?

A. No. We never used epoxies because of the problem of getting into the box.

Q. What about the two-element epoxy systems where you would actually cure them in place?

A. How are you going to get the package open?

An Analysis of Forced Convection Heat Transfer in High-Density Circuit Packages

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The results of an investigation of the cooling characteristics of high-density packaging of solid state logic circuits are presented. The analysis is based on the theory of single-pass air-cooled heat exchangers with uniform heat flux for laminar and turbulent flow. General expressions are derived which predict the amount of cooling air required on a normalized basis as a function of parameters such as average package "filling factor" for both the laminar and turbulent flow cases. The general expression has been successfully solved using IBM 704 and IBM 7090 Data Processing Systems. Several trial runs have been made with what is believed to be a representative range of values of wattage density, thermal resistance of circuit blocks, and other relevant parameters. The results show (as expected) that there exists an optimum package height (air duct length) for any given packaging density and wattage density which results in a minimum blower power. The expression for computing blower power as a function of required air flow and package parameters is developed. The analysis is sufficiently general to be adaptable to air flow predictions for a broad range of package configuration through which cooling air can be forced. An appendix is included which discusses the results of certain tests on a heat transfer model. The results of the tests appear to support the theory quite well, especially considering the relatively crude approximation to a uniform heat flux heat exchanger that the model represents. Curves presenting the experimental data are included, along with some air flow predictions for a hypothetical model for 90°, 100°, and 110°F air inlet temperature, and 60 mw logic block dissipation. The predicted air flow appears quite reasonable.

INTRODUCTION

THIS INVESTIGATION and analysis was undertaken to determine if a set of general design criteria for convective heat transfer in high-density circuit packages could be established. It was intended that the analysis be sufficiently general to be applicable to a broad range of packaging configurations. It appears that this objective has been at least partially achieved.

Since the inception of miniaturization, there has been some concern about the so-called "thermal barrier" which may or may not result when electronic devices are packaged evermore closely together. It has been argued that although the power dissipation of individual components in miniature and microminiature circuits is relatively much lower, the increased component density may result in average power densities comparable to or higher than with conventional packaging schemes. Furthermore, with some interim approaches based on the encapsulated building block utilizing discrete components, it has been feared that with the additional thermal resistance introduced by this encapsulant intolerably high component temperatures would result. It has been claimed that circuit building blocks, made up of single- or multiple-layer substrates with monolithic circuit elements, constitute a much more manageable configuration from the thermal standpoint since the sources of dissipation are located in direct contact (or nearly so) with cooling air.

However, there exists a school of engineering thought that claims the impossibility of adequately cooling high-density circuitry. This belief is based more on qualitative appraisals than on analysis and quantitative data. One factor which has been responsible for some confusion is the so-called "free air" or "still air" method for rating device thermal resistance. Since there is no common agreement concerning what constitutes a still environment (if such a condition actually ever exists) thermal resistance ratings on this basis are of little practical significance or value. In fact, there is always some air movement from natural convection, but natural convection is affected (in a complicated manner) by a multitude of factors. It is the low-velocity laminar flow due to natural convection that obviously is perfectly adequate in cooling a majority of isolated, discrete components. It is shown in this paper why laminar flow would be inadequate in most cases for cooling when a large aggregation of dissipative components are densely packaged, and that turbulent air flow in most cases will provide adequate cooling for the same configuration.

There is a second area of consideration of major importance when the so-called substrate circuit modules are employed. The maximum temperature of circuit elements on a substrate is not only a function of air flow characteristics but very strongly a function of the bulk thermal conductivity of the substrate material and the geometrical configuration of the dissipative circuit elements on the substrate surface. There is no longer a junction-to-case thermal resistance factor because the exposed surface is not isothermal. The thermal analysis in this case becomes more complex. In fact in certain cases an accurate or even approximate analysis requires a machine solution of the Fourier heat flow equation in three dimensions. The solution of this type of problem can be implemented by means of a mesh relaxation technique.

ANALYSIS

Basic Packaging Scheme for High Density

For purposes of analysis a basic packaging scheme based on a pluggable master card capable of holding a number of smaller pluggable cards was assumed. Each smaller card would hold a number of substrate circuit blocks. The smaller cards would be arranged on the master cards as shown in Fig. 1. The master cards would in turn be arranged so that the spacing would just allow clearance between the backs of the master cards and the tops of the smaller cards mounted on the adjacent

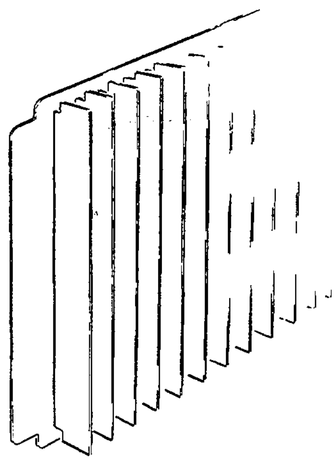


Fig. 1. Master card with pluggable card in place.

master card as shown in Fig. 2. The resulting arrangement would strongly resemble the core of a single-pass heat exchanger. With this arrangement, the direction of easy airflow is parallel to both master cards and master card sockets with second-level cards positioned parallel to the master card sockets (see Fig. 2).

Pluggable Card Array as a Normalized Heat Exchanger

In this study it was decided to make as general an analysis as possible with one basic assumption—that the package would be air cooled. Since it was apparent that the sizes of actual packages would differ and packaging geometries might also vary, it was decided to base this analysis on a normalized package volume (size) of 1 ft^3.

Two basic parameters are used to define the large-scale package geometry. They are:

1. L, the length of the package in the direction of air flow, and
2. γ, the volume filling factor which equals the ratio of volume of air space V_A to the total package volume of 1 ft^3 (V_0).

Figure 2 illustrates the package concept. The analysis reduced to finding the necessary airflow for maintaining certain component temperatures at a specified maximum value under the condition of a specified maximum inlet cooling air temperature.

Under conditions of a fairly uniform distribution of power dissipation throughout an array of logic cards, the hottest circuit blocks of a given type are assumed to be those located closest to the air exit. The particular component temperature of greatest interest is the junction temperature t_{jm} of the hottest logic inverter stage. The basic relationship is

$$t_{jm} = t_{im} + \Delta t_b + \Delta t_f + \Delta t_p \qquad (1)$$

where t_{jm} is the maximum junction temperature, t_{im} is the maximum air inlet

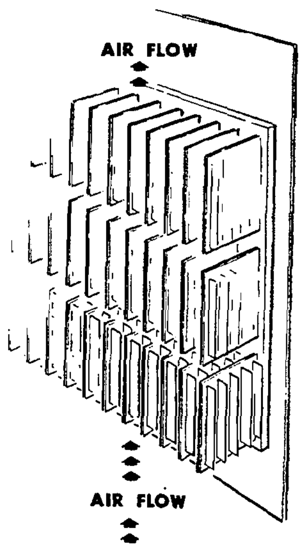


Fig. 2. Overall card packaging scheme.

temperature, Δt_b is the temperature rise of the air between inlet and outlet, Δt_f is the temperature rise across the boundary layer air film at the surface of the substrate and Δt_p is the temperature rise between transistor junction and cooled surface of substrate.

The temperature rise across the boundary layer film is given by

$$\Delta t_f = \frac{q}{h_f A_p} \tag{2}$$

where q is the dissipation of substrate in Btu/hr, A_p is the effective cooled surface area in ft^2, and h_f is the film heat transfer coefficient at the exhaust end in Btu/hr-ft^2-°F.

The temperature rise of the bulk air between inlet and outlet is given by

$$\Delta t_b = \frac{Q}{W c_p}$$

where Q is the average dissipation of the normalized array in Btu/hr-ft^3, W is the mass flow rate of air in lb$_m$/hr-ft^3, and c_p is the specific heat of air at constant pressure in Btu/lb-°F.

The temperature rise between the cooled surface of the substrate and the transistor junction is difficult to specify precisely because the substrate surface is not isothermal, and thus the surface temperature distribution will vary as a function of h_f. However, if the bulk thermal conductivity of the substrate material is sufficiently high, the whole substrate may be considered isothermal as a reasonable approximation so that a junction-to-surface temperature differential of a few degrees may be assigned to Δt_p. If this assumption cannot be made, the problem becomes much more complex.

The expression for T_{jm} can now be written as

$$t_{jm} = t_{im} + \frac{Q}{Wc_p} + \frac{q}{h_f A_p} + \Delta t_p \tag{3}$$

At any given position in a heat exchanger, the surface heat transfer coefficient, hx, is a function of air velocity for both laminar and turbulent flow. The laminar flow condition is considered first.

Laminar Flow Convective Heat Transfer

In dealing with forced convection, it is convenient to define a normalized measure of heat transfer N_{Nu} known as the Nusselt number:

$$N_{\mathrm{Nu}} = h_x \frac{D_e}{k} \text{ [dimensionless heat transfer factor]}$$

where h_x is the local surface heat transfer coefficient in Btu/hr-ft^2-°F at a distance x from the entrance end, D_e is the equivalent diameter of the duct in ft, and k is the bulk thermal conductivity of air in Btu/hr-ft-°F.

In the entrance region of a duct, flow characteristics gradually change from slug flow with a laminar boundary layer to either fully developed laminar flow, beyond the transition region, or to turbulent flow if the velocity exceeds a critical value. In the case of laminar flow, the boundary layer is theoretically of zero thickness at the entrance (slug flow) but builds up through a gradual transition to result in a parabolic velocity distribution which is characteristic of fully developed laminar flow. The effect of this flow is to cause the local heat transfer coefficient to be very high (theoretically infinite at the entrance) and to decrease asymptotically to a low value at the distance where laminar flow is fully established. Kays has found, by numerical methods, the variation of the local Nusselt number N_{Nu} as a function of a dimensionless distance factor[1]

$$\left(\frac{x}{D_e} \cdot \frac{1}{N_{\mathrm{Re}} N_{\mathrm{Pr}}}\right)$$

A plot of the results of this analysis for uniform heat flux is shown in Fig. 3.

By showing this variation on a log–log plot, two approximate exponential equations can be derived easily by observing that there are two regions of constant slope. The relations turn out to be

$$N_{\mathrm{Nu}} \approx \begin{cases} 1.18\left(\dfrac{x}{4R} \cdot \dfrac{1}{N_{\mathrm{Re}} N_{\mathrm{Pr}}}\right)^{-0.429} & \text{for } \left(\dfrac{x}{4R} \cdot \dfrac{1}{N_{\mathrm{Re}} N_{\mathrm{Pr}}}\right) \leqslant 0.05 \quad \text{(4a)} \\ 4.36 & \text{for } \left(\dfrac{x}{4R} \cdot \dfrac{1}{N_{\mathrm{Re}} N_{\mathrm{Pr}}}\right) > 0.05 \quad \text{(4b)} \end{cases}$$

where $R = D_e/4$ is the aerodynamic radius, [Duct Area/Duct Perimeter] [ft]; N_{Re} is the Reynolds number, [dimensionless group]; $N_{\mathrm{Pr}} = c_p\mu/k$ is the Prandtl

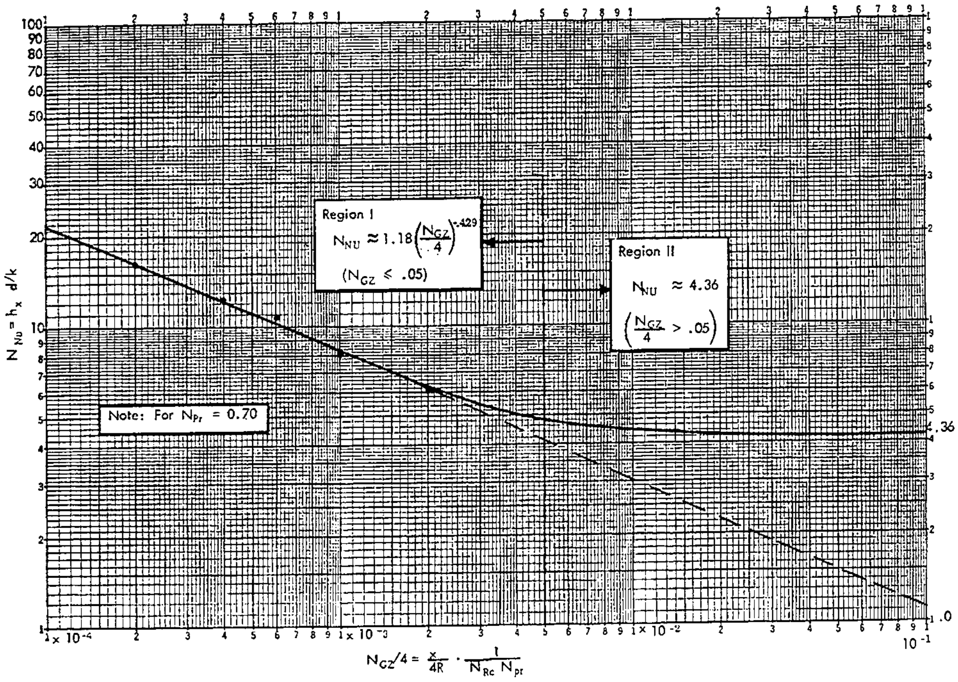


Fig. 3. Variation of local Nusselt number for laminar flow in a duct with heating from entrance and uniform heat flux (after Kays).

number, [dimensionless group], with μ equal to the absolute viscosity, c_p equal to the specific heat, and k equal to the bulk thermal conductivity.

These equations can be manipulated to give

$$h_f = h_x = \frac{1.18k}{4R}\left(\frac{L}{4R} \cdot \frac{1}{N_{\mathrm{Re}}N_{\mathrm{Pr}}}\right)^{-0.429} \tag{5a}$$

and

$$h_f = \frac{4.36k}{4R} \tag{5b}$$

for the same conditions specified as in (4) where $h_f = h_x$ when $x = L$, (L is the length of the air duct).

The Reynolds number N_{Re} is related to the mass flow rate of air and the geometry of the normalized package by

$$N_{\mathrm{Re}} = \frac{D_e(WL/\gamma)}{\mu}$$

where W is the mass flow rate in $\mathrm{lb_m/hr\text{-}ft^3}$, L is the length of the array in the direction of air flow, ft, γ is a dimensionless volume ratio, and μ is the absolute viscosity in $\mathrm{lb_m/hr\text{-}ft}$.

Since the Prandtl number N_{Pr} is 0.7 for air, Eqs. (4a) and (4b) can now be rearranged in the following form:

$$h_f = \frac{1.18k}{4R}\left[\frac{L}{0.7(16R^2L/\gamma\mu)}\right]^{-0.429} W^{0.429} \tag{6}$$

or

$$h_f = \frac{kW^{0.429}}{1.25R^{0.142}\mu^{0.429}\gamma^{0.429}}$$

and

$$h_f = \frac{4.36k}{4R}\ \text{[beyond transition point]}$$

Note that h_f turns out to be independent of the package air path length L for laminar flow and constant air flow W.

If Eq. (6) is substituted into Eq. (3):

$$t_{jm} = t_{im} + \Delta t_p + \frac{QW^{-1.0}}{c_p} + \frac{1.25qR^{0.142}\mu^{0.429}\gamma^{0.429}W^{-0.429}}{kA_p} \tag{7a}$$

which is valid for $L \leqslant 0.05\,(4\mathrm{R})N_{\mathrm{Re}}N_{\mathrm{Pr}}$. For $L > 0.05\,(4R)N_{\mathrm{Re}}N_{\mathrm{Pr}}$, Eq. (7b) is appropriate:

$$t_{jm} = t_{im} + \Delta t_p + \frac{QW^{-1}}{c_p} + \frac{4qR}{4.36kA_p} \tag{7b}$$

As a consequence of the independence of h_f from air path length L, t_{jm} will also be independent of L for a fixed air flow rate W. It turns out that this behavior is characteristic of laminar flow only.

Turbulent Flow Convective Heat Transfer

One feature which distinguishes convective heat transfer with turbulent flow is that h_x is independent of distance from the entrance. A transition length exists (about ten duct diameters) for the case of turbulent flow in which the flow may be initially laminar or turbulent, depending on the degree of turbulence of the inlet air.

The basic equation relating the film temperature riser to the heat transfer coefficient Eq. (2), also applies to the turbulent flow case. A semiempirical relation governing the normalized heat transfer coefficient, due to McAdams[2], is

$$N_{\mathrm{Nu}} = 0.023(N_{\mathrm{Re}})^{0.8} \cdot (N_{\mathrm{Pr}})^{0.4} \tag{8}$$

After rearrangement and substitution the surface heat transfer coefficient is found to be

$$h_f = 0.0144c_p\frac{(WL/\gamma)^{0.8}}{(4R)^{0.2}} \tag{9}$$

This equation should be compared to Eq. (6). Notice that h_f is no longer independent of L for the normalized heat exchanger, and that h_f is also a stronger function of W. The equation for the junction temperature at the exhaust end for turbulent flow can now be written as

$$t_{jm} = t_{im} + \Delta t_p + \frac{Q}{Wc_p} + \frac{q}{A_p\{0.0144c_p[(WL/\gamma)^{0.8}/(4R)^{0.2}]\}} \tag{10}$$

or

$$t_{jm} = t_{im} + \Delta t_p + \frac{Q}{Wc_p} + \frac{91.6(qR^{0.2}\gamma^{0.8}L^{-0.8})W^{-0.8}}{A_pc_p}$$

Comparison Between Laminar and Turbulent Flow Convective Heat Transfer

To compare laminar and turbulent flow transfer, it will be instructive to compare the respective equations for the normalized heat transfer coefficient N_{Nu}. For laminar flow there are Eq. (4) and

$$N_{\mathrm{Nu}} \approx \begin{cases} 1.18\left(\dfrac{X}{4R}\dfrac{1}{N_{\mathrm{Re}}N_{\mathrm{Pr}}}\right)^{-0.429} & \text{for} \quad \left(\dfrac{X}{4R}\dfrac{1}{N_{\mathrm{Re}}N_{\mathrm{Pr}}}\right) \leqslant 0.05 \quad \text{(4a)} \\ 4.36 & \text{for} \quad \left(\dfrac{X}{4R}\dfrac{1}{N_{\mathrm{Re}}N_{\mathrm{Pr}}}\right) > 0.05 \quad \text{(4b)} \end{cases}$$

and for turbulent flow

$$N_{\mathrm{Nu}} = 0.023(N_{\mathrm{Re}})^{0.8}(N_{\mathrm{Pr}})^{0.4} \tag{8}$$

In the case of turbulent flow, flow conditions in the entrance region (about ten or more duct diameters in length) may lie anywhere between laminar–transition and fully turbulent, depending on the flow characteristics and the turbulence of the incoming air. In most cases the incoming air flow can be considered laminar so that for a distance of ten or more duct diameters, Eq. (4a) will apply; Eq. (8) will apply at all distances greater. If the numerical value of $N_{\mathrm{Pr}} = 0.7$ for air is substituted into Eq. (4a) it can be rewritten as

$$N_{\mathrm{Nu}} = 1.83\left(\frac{R}{X}\right)^{0.429} \cdot (N_{\mathrm{Re}})^{0.429} \tag{11}$$

for laminar flow before transition, and Eq. (8) can be rewritten as

$$N_{\mathrm{Nu}} = 0.02(N_{\mathrm{Re}})^{0.8} \tag{12}$$

for turbulent flow beyond the transition region.

Examination of Eq. (11) reveals that the surface heat transfer coefficient near the entrance of a duct can be quite high, varying as the -0.429 power of the distance from the entrance. This means that, for any given Reynolds number less than a "critical" value, the heat transfer coefficient will exponentially decrease until it reaches an asymptotic value beyond the transition length. For N_{Re} greater than the "critical" value, N_{Nu} will decrease exponentially until the distance is reached where the flow becomes turbulent; but with the onset of turbulence beyond the laminart-ransition region, the value of N_{Nu} will jump up to some constant value determined by Eq. (12).

As an example, assume a flow condition with $N_{\mathrm{Re}} = 5 \times 10^3$. The position of interest is where $X/D_e \geqslant 10$ or $X/R \geqslant 40$. If the values are substituted into Eqs. (11) and (12), respectively, it turns out that N_{Nu} is equal to 14.5 at a point just before the flow becomes turbulent and jumps up to 18 for the remaining length of the duct. Observe that at higher values of N_{Re} the difference in N_{Nu} will be even more pronounced. The implication here is that under certain conditions (with turbulent flow), it is possible for substrate circuit blocks located at some point between inlet and exhaust end to be hotter than blocks of the same type at either end.

SOLUTION

Minimum Necessary Air Flow for Turbulent Flow for the Normalized Package

Now the question arises—given certain requirements such as the maximum allowable junction temperature on a certain type of circuit substrate, the maximum room ambient temperature, the average power of the package in watts per cubic feet and the power of the particular substrate circuit in question, what is the required air flow, W in pounds per hour? The variation of W as a function of air path length L and package filling factor γ is of interest.

Equation (10) can be rearranged to read:

$$c_p(t_{jm} - t_{im} - \Delta t_p)W - \left[\frac{q(4R)^{0.2}}{0.0144A_p(L/\gamma)^{0.8}}\right]W^{0.2} - Q = 0 \qquad (13)$$

where c_p is the specific heat of air in Btu/lb-°F, A_p is the effective surface area of the substrate in ft^2, q is the heat generated by individual substrate in Btu/hr, Q is the total heat generated by a 1-ft^3 package in Btu/hr-ft^3, W is the mass flow rate of cooling air in lb/hr-ft^3, R is the aerodynamic radius of the ducts in ft, t_{jm} is the maximum allowable junction temperature on the substrate in °F, t_{im} is the maximum inlet air temperature in °F, Δt_p is the temperature differential between the junction and the substrate surface in °F, L is the path length of air for the entire package in ft, and γ is the package filling factor (a dimensionless volume ratio).

This equation can be simply solved for W as a function of γ and L by either graphical or digital-machine techniques. Once W is known, other related quantities such as N_{Re}, N_{Nu} in cfm, Δt_f, Δt_b, $(\Delta t_b = Q/WC_b - t_{im})$, and U_b can be readily calculated. Of particular interest is the air horsepower loss due to friction and the entrance-exit velocity head (kinetic energy) losses. The air horsepower is related to W by

$$\text{H.P.} = \frac{H_L W}{33 \cdot 10^3 (60)^5} + \frac{H_e \cdot W}{33 \cdot 10^3 \cdot (60)^5} \text{ [horsepower]}$$

where H_L is the frictional head loss in ft of air, H_e is the kinetic energy head loss at entrance and exit in ft of air, and $33 \cdot 10^3 \cdot (60)^5$ is the units conversion factor in ft-lb-sec²/hr³-ft³.

However

$$H_L = \frac{fLU_b^2}{4R \cdot 2g} \qquad H_e = \frac{U_b^2}{2g} \qquad U_b = \frac{WL}{\rho\gamma}$$

where f is the estimated friction factor (dimensionless), U_b is the bulk air velocity in ft/sec, g is the acceleration due to gravity in ft/sec², and ρ is the mass density of air in lb/ft³.

After terms are collected and the numerical value of 64 is substituted for $2g$.

$$\text{H.P.} = \frac{W^3L^2(fL + 4R)}{\rho^2\gamma^2R \cdot 4 \cdot 64 \cdot 33 \cdot (60)^5 \cdot 10^3} \tag{14}$$

Observe how the required air horsepower varies as a function of γ and L. Figure 4 shows the general nature of this relationship. This behavior was determined by solving Eqs. (13) and (14) by an IBM 7090 Data Processing System for a typical set of conditions (see Appendix A).

Also observe that for any given γ, there is an optimum air path length L but not a very pronounced one. Also, the air horsepower is not strongly dependent on γ until γ becomes less than 0.1, whereupon the required horsepower increases very rapidly as γ decreases further. However, the energy loss usually incurred by air filters has so far been neglected. To be able to appraise the effect of air filters, a plot of a typical variation of required air flow in cubic feet per minute as a function of L (γ = constant) and variation of velocity U_b as a function of L are shown in Fig. 5. The very rapid increase of required air flow for $L < 2$ ft indicates that the actual total required blower horsepower would increase in much the same manner because the frictional losses become almost negligible. Since the velocity is nearly

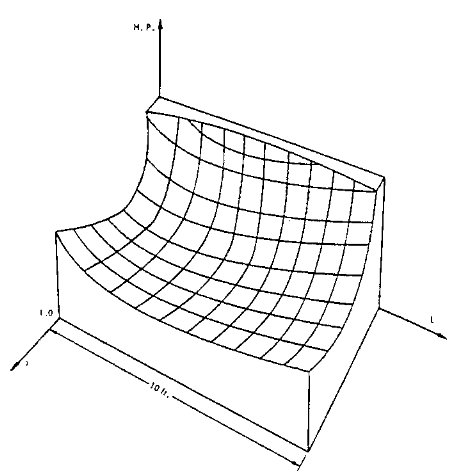


Fig. 4. Air horsepower as a function of packaging height, L, and filling factor, γ_A. ($1 \leqslant L \leqslant 10, 0.1 \leqslant \gamma \leqslant 1.0$.)

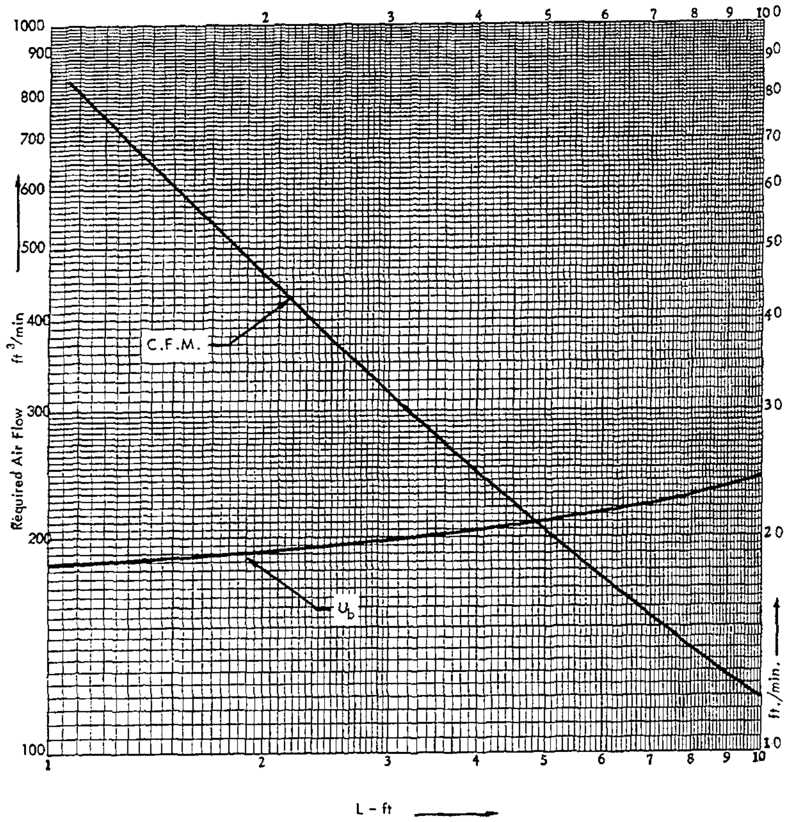


Fig. 5. Typical variation of required air flow as a function of air path length; $\gamma = 0.8$ for a 1-ft³ package and typical variation of air velocity U_b for the same conditions.

constant, frictional losses change little with changes in L. The result is that filter and velocity head losses will account for almost all the energy losses for small L. If losses incurred by air filters were to be included in the equation for air horsepower [Eq. (14)], the minimum horsepower would occur at a larger value of L for any given value of γ. (See Appendix A for additional discussion.)

Rules for Optimizing Forced Connective Cooling

It is assumed in this paper that the cost of cooling is minimized if the required blower horsepower is minimized. The acoustical noise is also apt to be at a reduced level when the blower power is a minimum. The analysis presented here indicates that to minimize required horsepower a packaging configuration which yields a fairly low filling factor γ is necessary. Most of the volume of the package should be taken up by cards and components leaving about 10% (or slightly less) of the total package volume as air-duct space. Unfortunately, a γ of less than 0.7 may prove to be difficult to achieve in practice. If the energy loss of the air filters is taken into account, the blower horsepower required will be minimized for a package air path length somewhere between 4 and 8 ft. The optimum value of L increases as the pressure drop across the air filter increases (see Appendix A). The optimum value of L is found to be larger as γ increases.

The exponential decrease of h_x in the transition (inlet) region of a duct is undesirable. This effect may be eliminated, or at least minimized, by artificially inducing turbulence at the entrance of each duct (card column). The results of an experimental investigation of this effect is included in Appendix B.

What this means is that, from the standpoint of initial cost, a packaging arrangement that results in the cooling air being passed in series over a number of master cards ($L = 4$ ft) is apt to be lowest in cost. This criterion is probably of secondary importance compared to the criteria imposed by serviceability considerations.

CONCLUSIONS

The question posed at the initiation of this investigation was—Can a set of general ground rules be developed to serve as a guide for evaluating the forced convective heat transfer performance of various high-density logic circuit packages? It may indeed be concluded that some general design rules have been formulated as a result of evaluating the implications of the various package parameter relationships.

The hottest circuit substrate blocks of a given type may actually be located at some point between inlet and exhaust end of the package when the air velocity exceeds the critical value necessary for turbulent flow to develop. This effect may be avoided by ensuring a sufficient degree of inlet air turbulence. Because of the many conflicting requirements (e.g. manufacturing and servicing) for circuit packaging, it does not seem likely that cooling can be optimized in the sense of minimizing the blower power. But at least the degree of nonoptimization can be determined, and the effects of various changes in geometry can be predicted.

APPENDIX A: AIR FLOW PREDICTION FOR SEVERAL REPRESENTATIVE PACKAGING CONFIGURATIONS

The junction temperature of a given type of substrate circuit block located at the exhaust end of the package is given by

$$t_{jm} = t_{im} + \Delta t_p + \frac{Q}{Wc_p} + \frac{91.6qR^{0.2}\gamma^{0.8}L^{0.8}W^{0.8}}{A_pc_p} \tag{10}$$

Since t_{jm} and t_{im} are known and the variation of required air flow W as a function of R, γ, L, Δt_p, A_p, Q, and q is desired, Eq. (10) can be rearranged into a more useful form:

$$c_p(t_{jm} - t_{im} - \Delta t_p)W - \left[\frac{q(4R)^{0.2}}{0.0144A_p(L/\gamma)^{0.8}}\right]W^{0.2} - Q = 0 \tag{13}$$

The machine implementation of the solution of this equation for W proved to be quite simple. It was decided to treat L and γ as the two principal variables and hold all other parameters constant during each run.

Although $4R(D_e)$ is actually a variable (which is a function of γ), $(4R)^{0.2}$ only changes by a ratio of 1.6 as γ changes from 0.1 to 1.0. Hence R was treated as a constant in the program. An exact relation for R as a function of γ for a perfectly rectangular duct is given by:

$$R = \frac{b}{2}\left(\frac{\gamma}{\gamma + b/d}\right)$$

where b is the height of the pluggable card in ft, d is the spacing between pluggable cards in ft, and γ is the filling factor. Thus, a more accurate relation for W would be

$$c_p(t_{jm} - t_{im} - \Delta t_p)W - \left\{\frac{q[2b(\gamma/(\gamma + b/d))]^{0.2}}{0.0144A_p(L/\gamma)^{0.8}}\right\}W^{0.2} - Q = 0 \quad (13)$$

L underwent increments in steps of 1 ft from 1 to 10 ft, while γ was increased from 0.1 to 1.0 in 0.1 steps. The full range of L was covered for each increment of γ.

In addition to computing the value of W for each combination of L and γ, the corresponding air horsepower was computed from the following relationship:

$$\text{H.P.} = \frac{W^3L^2(L + 4R)}{\rho^2\gamma^2 \cdot 4R \cdot 64 \cdot 33 \cdot (60)^5 \cdot 10^3} \text{ [horsepower/ft}^3\text{]} \quad (14)$$

To be sure that Eq. (13) was predicting values of W within the valid range ($N_{\text{Re}} > 2300$), the value of N_{Re} was computed for each W. N_{Re} is related to W by:

$$N_{\text{Re}} = \frac{(4R)(WL/\gamma)}{\mu}$$

As a further check on the reasonableness of the predicted air flow W the additional related quantities U_b, cfm, Δt_f, Δt_b, and H_s (total head loss, inches of water) were computed. These quantities are given by the following:

$$U_b = \frac{WL}{\rho\gamma \cdot 60} \text{ [ft/min]}$$

$$cfm = \frac{W}{\rho \cdot 60} \text{ [ft}^3\text{/min]}$$

$$\Delta t_b = \frac{Q}{Wc_p} \text{ [F}^\circ\text{]}$$

$$\Delta t_f = \frac{q}{h_f A_p} \text{ [F}^\circ\text{]}$$

$$\rho(\text{water}) = 62 \text{ lb/ft}^3 \text{ [mass density of water]}$$

and

$$H_s = \frac{(\text{H.P.}) \cdot 12 \cdot 33 \cdot (60)^2}{W \cdot \rho(\text{water})} \text{ [inches (of water)]}$$

To determine if the packaging scheme for miniaturization (as originally conceived) could be cooled with a "reasonable" air flow, several runs (on the IBM 7090) were made using the following values for the pertinent parameters:

$\underset{\sim}{Q} = 1060$ Btu/hr-ft^3	$k = 0.016$ Btu/hr-°F
$R = 0.016$ ft (held constant)	$c_p = 0.237$ Btu/lb-°F
$A_p = 1.0 \times 10^{-3}$ ft^2 (area of substrate)	$\mu = 0.046$ lb/hr-ft
$q = 60$ (mw) (dissipation of logic inverter substrate)	

Three values of t_{im} were chosen, namely, 90°, 100°, and 110°F. It was felt that these values would cover the range of any likely maximum machine ambient temperature. Figure A1 shows the computed variation of required air flow in cubic feet per minute as a function of L for $\gamma = 0.8$ and 0.2. The advantage of a low-value filling factor γ is obvious. Notice also the increase of required air flow as a result of increasing the ambient temperature t_{im}.

To show the effect of decreasing the effective cooled surface of the substrate A_p while keeping its dissipation constant and also keeping the average package dissipation constant, a plot of required cooling air flow *vs* L for $\gamma = 0.2$, $\gamma = 0.8$, and $A_p = 0.5 \times 10^{-3}$ ft^2 is shown in Fig. A2. Here the only difference is the

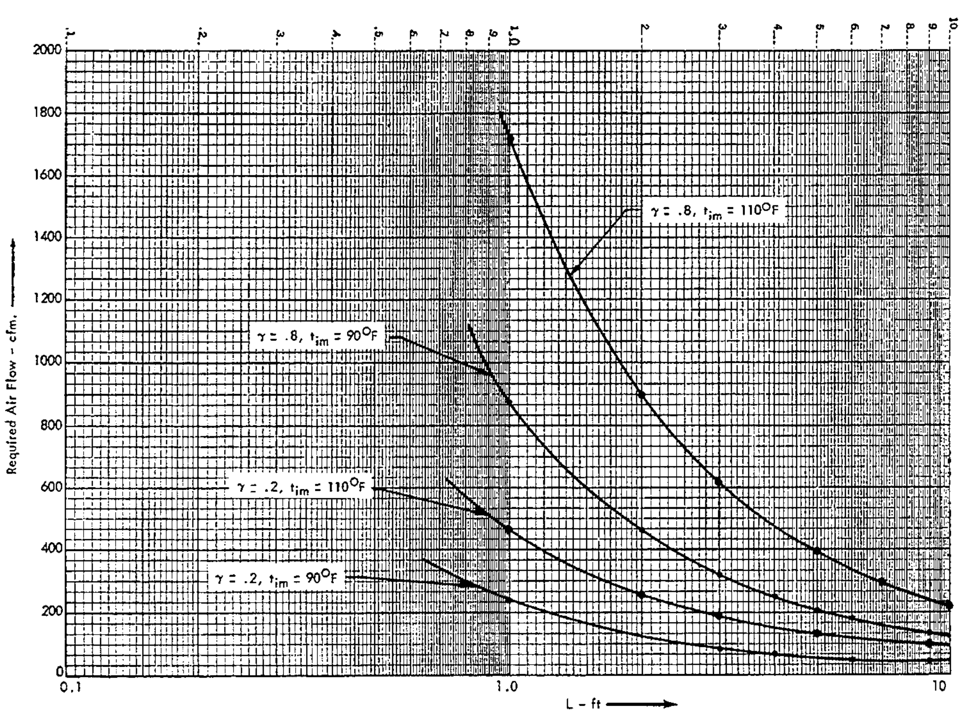


Fig. A1. Required air flow as a function of package height L for turbulent flow. $Q = 310$w/ft^3; $q = 62.5 \times 10^{-3}$ w; $A_p = 1.0 \times 10^{-3}$ ft^2 (0.380 × 0.380 substrate); $R = 0.016$ ft (duct aerodynamic radius); $t_{jm} = 140$°F $= 60$°C.

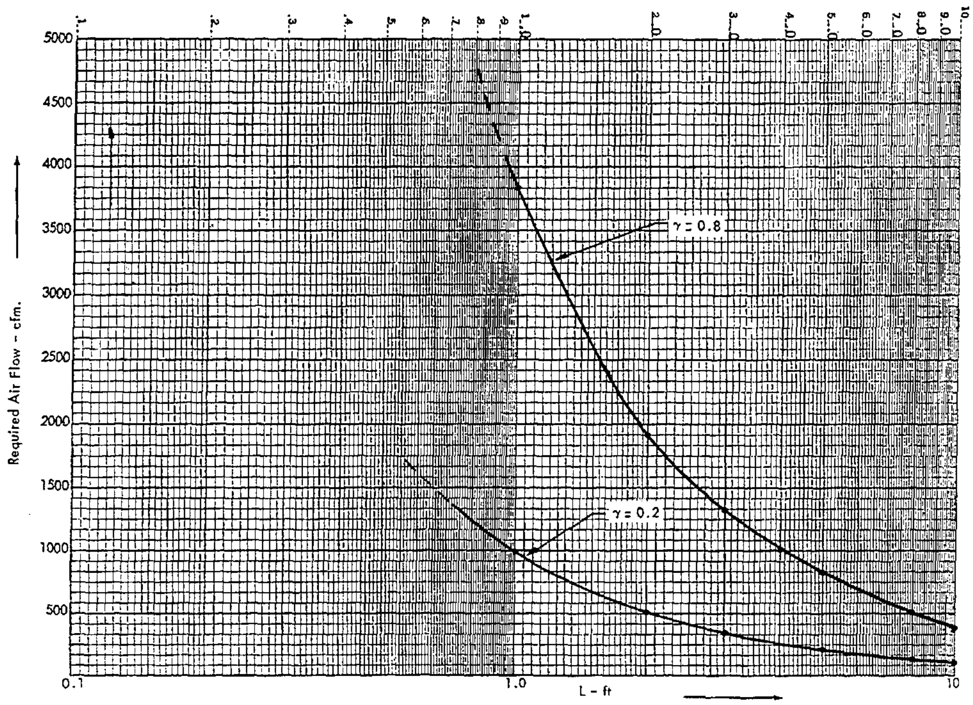


Fig. A2. Required air flow as a function of package height L for turbulent flow. $Q = 310$ w/ft^3; $q = 62.5 \times 10^{-3}$ w; $A_p = 0.5 \times 10^{-3}$ ft^2; $R = 0.016$ ft; $t_{im} = 110°$F; $t_{jm} = 140°$F $= 60°$C.

reduction of A_p to half that for the curves in Fig. A1. Only the required air flow for 110°F ambient is shown for this case.

The advantages of having a larger effective cooled surface area for the substrate are obvious. Conversely, reduction of the dissipation or an increase in area of the substrate will result in almost equal percentage reduction in the required air flow.

APPENDIX B: RESULTS OF TESTS ON A FORCED CONVECTION HEAT TRANSFER MODEL

In the early stages of this investigation it was decided to build an air-cooled heat transfer model to perform some rough experimental checks on the exponents of U_b in the equations for N_{Nu}. It was felt that measurements on such a model would reveal any large performance deviations for this type of heat exchanger (nonuniform heat flux) from that expected from the theory for uniform heat flux exchangers.

Since no substrate blocks were available in quantity at the time construction of the model was initiated, it was decided to populate the whole model package with $\frac{1}{4}$-w resistors as a substitute. A master card was utilized which had space available for 8 pluggable cards. Each pluggable card held 18 resistors, each dissipating about 100 mw. The pluggable cards were soldered onto the master cards by utilizing a solder bead along special-wide wiring pattern lands.

The master cards in the model were clamped in a holder with a spacing of about 1 in. between master cards with 15 master cards per holder. Three groups of master cards were supported in a frame in a manner similar to that shown in Fig. 2. The whole array of cards was enclosed in a tight fitting cardboard duct. The inlet end was connected to a blower through a vaned plenum. The outlet end was left open.

The air velocity was controlled by a variable throttling aperture at the intake of the blower. The air velocity was measured at the exhaust end by averaging several readings taken with a "Velometer" velocity probe. In this way the variable throttling aperture was calibrated for constant blower rpm.

It was decided to measure the surface temperature of a resistor at the entrance end, at the exit end, and at a point about 8 in. from entrance. In each case, the surface temperature was monitored by a glued-on thermocouple as the bulk air velocity U_b was incremented from about 50 ft/min to about 875 ft/min (the maximum velocity obtainable). Also monitored was the inlet air temperature and exhaust air temperature.

Since the heat transfer coefficient h_f is related to the temperature differential between component and average bulk air adjacent to the component by

$$h_f = \frac{q}{\Delta t_f A_p}$$

where $\Delta t_f = t_p - t_b$, a plot of Δt_f *vs* U_b will show the nature of the variation of h_f or N_{Nu} as a function of U_b. Figures B1, B2, and B3 show the variation of measured Δt_f as a function of U_b. Figure B1 reveals that there are essentially two regions of interest. At velocities less than about 200 ft/min, Δt_f and, consequently, N_{Nu} are essentially constant. This behavior probably corresponds to the region of Fig. 3 where $[(X/4R) \cdot (1/N_{\text{Re}}N_{\text{Pr}})] > 0.05$. The exponent of U_b gradually approaches -0.48 for higher velocities, which leads one to suspect that for U_b greater than 200 ft/min, this component (resistor) would be in the laminar transition region.

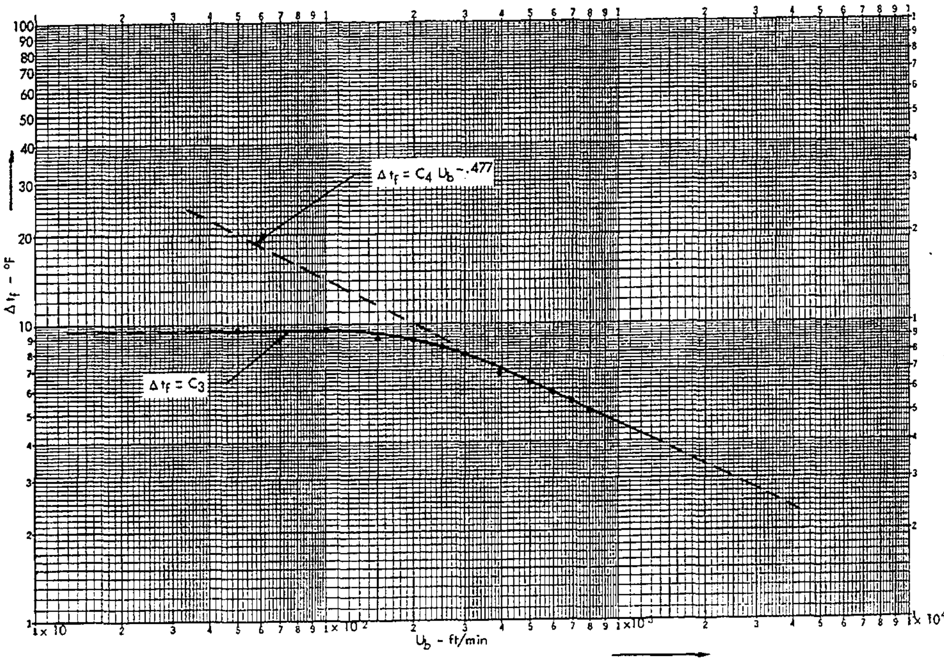
Examination of Fig. B2 reveals two separate regions, with the critical velocity again about 200 ft/min. In this case, the limiting exponent of U_b turns out to be about -0.71. This value corresponds closely to -0.8, which might be expected from the McAdams relation,

$$N_{\text{Nu}} = 0.023(N_{\text{Re}})^{0.8} \cdot (N_{\text{Pr}})^{0.4}$$

which is valid for turbulent flow.

The behavior of Δt_f shown in Fig. B3, for the component located 8 in. from the air entrance, is somewhat more difficult to interpret and evaluate. For velocities less than 100 ft/min, there appears to be no change in Δt_f, which indicates fully developed laminar flow. At higher velocities, especially above 400 ft/min, Δt_f seems to drop off with an exponent for U_b of about 0.4 which indicates laminar–transition flow.

There does not seem to be an adequate explanation for the sudden rise in Δt_f as U_b increases above 100 ft/min. The unexpected behavior of Δt_f in the range



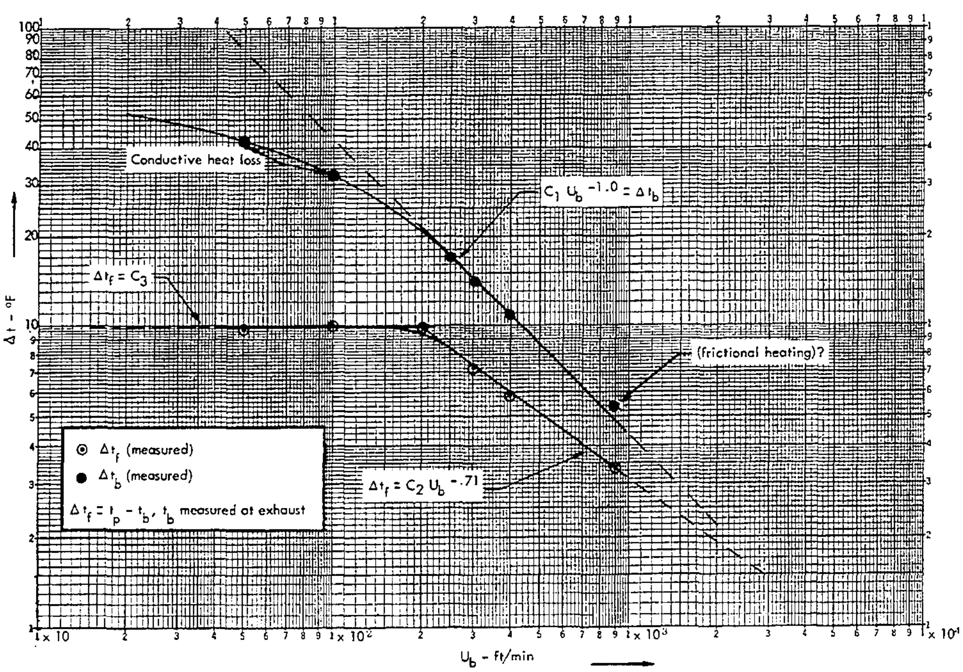


Fig. B2. Film temperature rise and bulk air temperature rise as a function of air velocity U_b, measured at exhaust end, 2.2 ft from entrance.

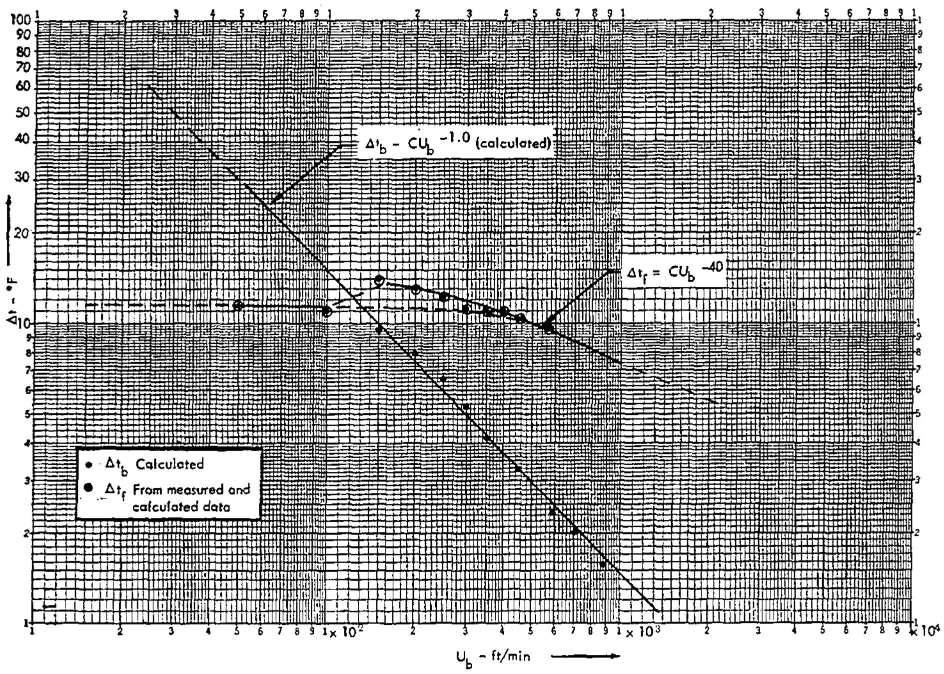


Fig. B3. Film temperature rise, t_f, and bulk air temperature rise as a function of air velocity U_b, measured at 8 in. from entrance.

100 ft/min $\leqslant U_b \leqslant$ 400 ft/min may be attributable to the method of measurement of Δt_b (that is, the temperature rise of the bulk air between the entrance and the point in question). The Δt_b utilized in computing Δt_b for this component was obtained by multiplying the total Δt_b for the entire array by the fractional part of the duct length to this component. Conducted heat loss effects (heat conducted through the cards) and nonuniformity of heat dissipation might have caused the calculated value of Δt_b at this station to be in error.

If it were assumed that the true behavior of Δt_f was shown in Fig. B3 by the dotted line in the range 100 ft/min $\leqslant U_b \leqslant$ 400 ft/min, then the transition between fully developed laminar and laminar–transition flow would have occurred at about 400 ft/min at this station. Apparently, even at the highest velocity (875 ft/min), full turbulence did not develop at this station since the limiting slope on the log–log plot seems to be about -0.4, which is about what one would expect for laminar–transition flow. An examination of Fig. 3 reveals that the laminar transition length is directly proportional to N_{Re} and hence to U_b. Therefore, it is reasonable to expect Δt_f to be constant out to higher velocities for stations further removed from the duct entrance, provided the flow does not become turbulent.

REFERENCES

1. W. H. Giedt, *Principles of Engineering Heat Transfer*, pp. 151, 152.
2. *Op. cit.*, p. 168.

DISCUSSION

Q. (L. V. Larson, General Electric Co., Coshocton, Ohio) You certainly have a really penetrating analysis of this air-flow transfer situation and I am sure it provides a lot of design data that people could take advantage of. I believe in your analysis that you have assumed constant ambient conditions (i.e., room air temperature and humidity). I wonder if you could comment on the possible effect of variation in humidity on some of the results that you have?

A. I didn't investigate the effects of humidity, but I suspect it would be negligible since the proportion of weight of water in a given volume of air is quite small on a weight percentage basis, so I suspect that the bulk thermal capacity and bulk thermal conductivity of air doesn't vary much as a function of humidity. Of course, since altitude affects air density so will it affect conductivity and thermal capacity, which are functions of density. Altitude effects can be taken into account simply by using the values of density, conductivity, and thermal capacity for the particular altitude in question.

Q. (Juris Eksteins, Litton Systems, College Park, Md.) Have you considered the density to be constant throughout the package?

A. Yes. The density was considered as being constant because compressibility effects are small at the relatively low velocities normally encountered in the situations considered here.

Q. Density will decrease or the specific volume will increase as temperature goes up, and this will effect the pressure drop.

A. That is a correct statement for the general case, however, when the temperature rise is small (say in the order of 10°F), the density change is small enough to neglect. I assumed that it was constant because this makes the analysis much simpler.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) I would like to have your comments on a number of the effects of other modes of heat transfer on the type of problem that you are investigating, particularly natural convection at right angles to the flow path, heat transfer by conduction from components to the wiring panel, and the radiation effect from the loads. Is there a significant temperature difference predicted if these effects are taken into account?

A. I didn't investigate the effects of the factors you mentioned. As you may have observed from some of the plots of bulk air temperature rise *vs* air velocity, there is a conductive heat loss which becomes appreciable at very low air velocities.

Q. If you had the fan turned off, you would still get heat transfer by natural convection. With the fan on, what effect does this natural convection have, if any?

A. If the array is vertical you will have natural convection, probably with laminar flow, the velocity of which may be measured. If we know what the average velocity is, the internal flow characteristics may be estimated from the relationships I have shown here. Then the heat transfer coefficients may be determined for various positions (i.e., you will probably still have entrance region effects, etc.). The flow conditions with natural convection predominating are very much influenced by geometric considerations and in most cases very difficult to predict. If the array is horizontal, there will be no through air flow due to natural convection with the fan off. With air flow under forced convection with velocity sufficiently high to be of much use in cooling, any natural convection is so small as to be undetectable and it would have no discernible effect.

Transient Thermal Analysis of the Weld-Pak Package

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This paper presents a transient thermal analysis of a weld-pak package. Included in the presentation is introductory matter concerning the weld-pak technique, designed to produce densely packed modules, a discussion of the thermal circuit and associated equations, and a sample problem in which thermal transients for complex assemblies are evaluated using the shorthand of an analog thermal circuit.

INTRODUCTION

THE "WELD-PAK" technique of packaging produces modules of densely packed standard components. In low-power-dissipation assemblies, the tested assembly is usually encapsulated with a plastic to provide lightweight but firm support for the components. When the technique is used to package power circuits, the mechanical support member must be replaced with a higher thermal conductivity material such as aluminum or magnesium to allow removal of the heat generated without excessive temperature gradients. The determination of the effectiveness of the support member as a heat remover involves evaluation of the thermal gradients from the heat sources to some known temperature point, such as temperature of the ambient air or liquid coolant. If the equipment is called upon to operate for long periods of time, the steady state evaluation of convection, radiation, and conduction heat transfer provides a sufficient information as to the adequacy of the thermal design. However, when the time of operation is short and the only available heat sink is the thermal mass of the equipment and adjacent structure, a transient analysis must be made.

Electrical analogs using resistance–capacitance networks provide direct duplication of the system response with suitable scale factors, and also simple schematic representation of the problem. Simulation by the electrical analog does, however, present limitations when nonlinear heat transfer modes are encountered. If the response of the electrical analog is determined analytically by difference equations substituted for the differential equations, these nonlinearities can be handled by re-evaluation of the parameters at each increment of time difference. The equivalent electrical analog permits preparation of the necessary circuit equations from simple diagrams of the thermal system. Either loop or nodal equations will provide solutions but the nodal summation of heat flows is usually preferable.

PREPARATION OF THE THERMAL CIRCUIT AND EQUATIONS

The thermal circuit should initially be prepared to include all heat sources, thermal resistances in the direction of heat flow, thermal masses, and known temperature points in the system. This is then simplified so that unknown temperature points, which are of interest, are at nodes of the circuit. The symbols and nomenclature used are shown in Table I.

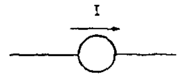
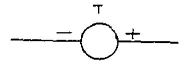
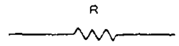
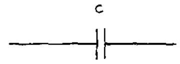
The difference equations sum the heat flow at each node. For small time increments, the heat flows at any node are dependent upon the temperatures at the adjacent nodes and any heat source connected to the node. This permits simple equations with constant coefficients.

SAMPLE APPLICATION

The electronics of a typical missile guidance system consists of many weld-pack modules. These modules are mounted on a water-cooled cold plate, which is supplied with chilled water up until missile launch. Most of the heat dissipated is removed by conduction to the cold plate. With continuous operation of the electronics, the cooling-water mean temperature will stabilize between the entrance and exit temperatures. In a similar manner, the cold-plate-metal temperature and all elements of the electronics will also stabilize at various levels above the mean water temperature. The magnitude of the difference between the temperature at any point and the mean water temperature will be dependent upon the heat flow rate from the point to the water and the thermal resistance along the path.

At missile launch, this picture is changed since a continued supply of chilled

TABLE I

Quantity	Symbol and Nomenclature	Typical Units	
Temperature source	I 	°F	°C
Heat source	T 	Btu/hr	w
Resistance	R 	°F-hr/Btu	°C/w
Capacitance	C 	Btu/°F	w-sec/°C

water is no longer available through the umbilical connection. At this time, the water in the system is trapped and held within the plate. The water is still capable of absorbing heat as before, however, with no circulation, its mean temperature will begin to rise. This rise in mean water temperature will further manifest itself by causing temperature increases throughout the electronics. This increase in temperature after launch could cause malfunction of the system if the thermal stress at any component caused excessive drift or complete loss of function.

In the development of this equipment, one of the modules contained a high-dissipation power amplifier utilizing two germanium transistors for the last stage. (The circuit has since been modified to allow use of silicon transistors, but the earlier version is discussed here.) The combination of high power density and low maximum temperature limitations inherent with germanium transistors made this module a critical one requiring detailed analysis.

The power amplifier assembly consisted of two machined housings, containing most of the circuit components, and two transformers. These four items are bolted to a common base plate and the welded circuit wiring is attached. One of the housings contained most of the components including two Minneapolis-Honeywell 3N50 transistors. Figure 1 shows this housing and its associated heat sources and heat flow paths. The transistors and their insulating mica washers are shown in detail. Heat dissipated within a transistor passes from the semiconductor junction to the outer surface of the enclosing can. This portion of the heat flow path is evaluated by transistor manufacturers and usually is a specification or catalog information item. The normal units are degrees centigrade per watt of dissipation.

Heat may leave the transistor cans by several paths. The major path is by conduction downward from the base or mounting surface of the transistor. The minor paths are convection and radiation heat transfer from the exposed surfaces of the cans. (These paths were essentially eliminated in later designs when a foam encapsulant was added to the volume over the transistor cans.) These minor paths may or may not be appreciable depending upon the factors of the surrounding air and wall temperatures and air pressure. In the conduction path, heat must pass through several elements, as indicated in Fig. 1. Since the bottom surface of the transistor and the upper surface of the mica are not perfectly flat surfaces and therefore not in perfect intimate contact, some allowance must be made for the thermal resistance present. Similar interface resistances are present in all surface contacts along the path to the cooling water. This interface or contact resistance has been evaluated both by literature search and by testing. Details are not included here but the list of references includes the applicable documents. In between these interfaces, the flow is by simple conduction through the particular material. The primary complexity encountered here is in the evaluation of the mean path length and cross-sectional area available for heat flow in the complex configuration of the housing.

The elements along the path from transistors to cooling water also possess capacitive qualities. In steady state or equilibrium heat flow analysis, this effect can be neglected since there is no change in temperature with time. However, in the transient analysis, all temperature changes with time are the result of a gain or

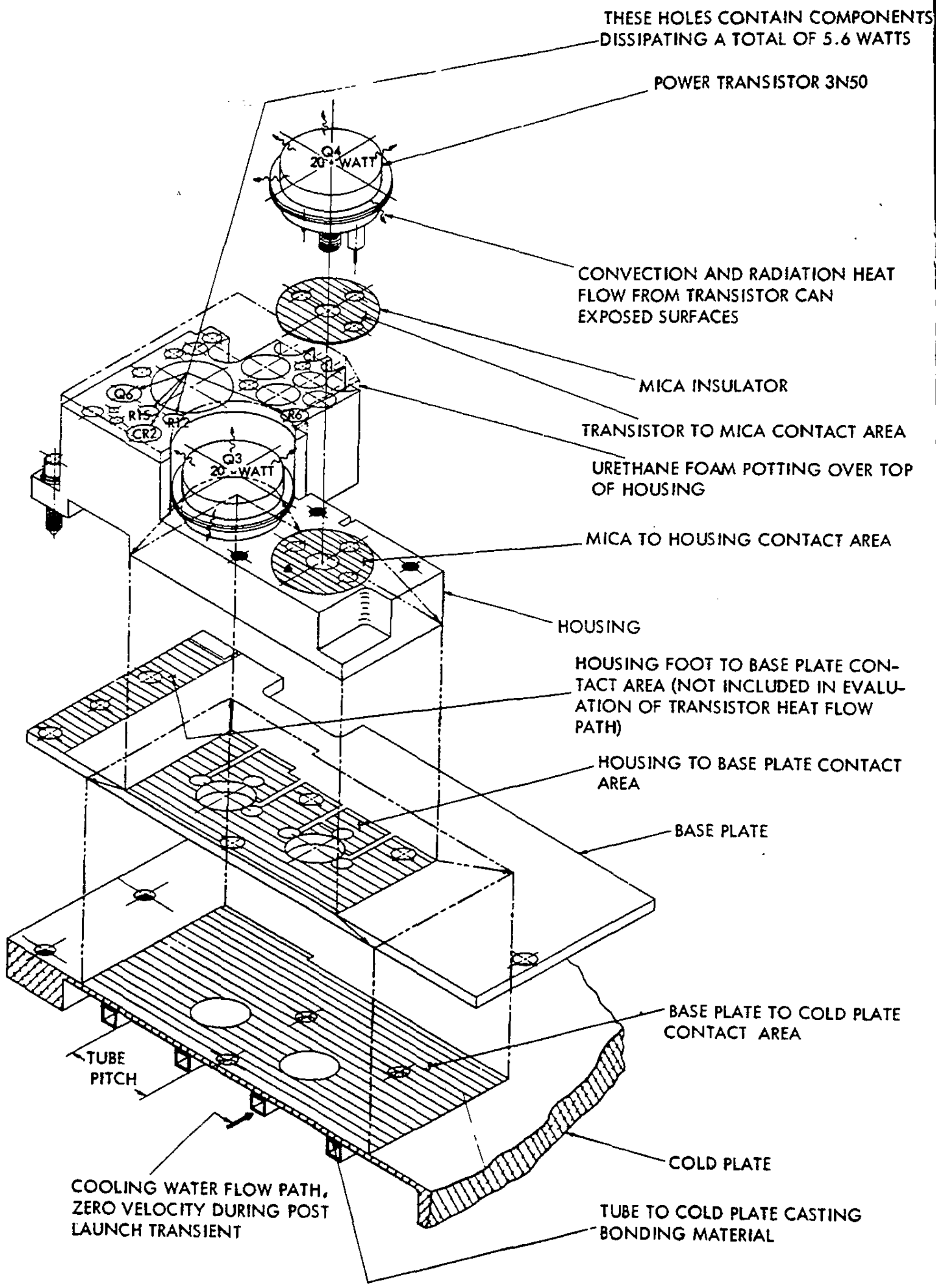


Fig. 1. Power-buffer amplifier heat flow paths.

loss of sensible heat in the element. The major capacitive elements in the transistor to cooling water path are the transistors themselves, the housing and base plate, and the cold-plate assembly of metal and water.

The overall thermal system was further defined by analysis and tested by others, to the point that the following information was known.

1. Aerodynamic heating during powered flight would cause equal maximum ambient air and surrounding wall temperatures which could be expressed as time functions.
2. Increasing altitude would cause a known pressure decrease with time.
3. Mean water temperature at launch was known.
4. Cold-plate performance in terms of unit thermal resistance (°C-in.^{2}/w) was known.
5. Power dissipations for all components were known. (Both power transistors dissipated equal power.)

With the physical configuration of the module and the additional thermal system information above, the thermal circuit for the one module was prepared and is shown in Fig. 2. The dissipation of each power transistor is shown by a current source I_j.* Heat from this point must pass through the internal resistance R_1 of the transistor to reach the outer surfaces of the transistor can. At this point, heat may be stored in the thermal mass, C_p or leave by one of the three thermal paths shown by the resistances R_2, R_c, and R_r. The latter two represent the convection and radiation paths to ambient air and the surrounding walls of the compartment. Since the surrounding air and wall temperatures were specified as equal for the maximum condition, these two resistances were shown connected to the common temperature source T_a. The conduction path resistance R_2 shows the path from the mounting surface of the transistor through the mica electrical insulator into the adjacent metal surface of the housing.

Both power transistors are represented by thermal circuits identical both in form and values. At the top of the metal housing, heat from both power transistors is conducted downward into the mass of the housing through the conduction resistance R_3. At this point, the heat from the other smaller components, which are lumped together as one heat source I_2 enter through their mean thermal resistance path R_4. Again, heat may be stored at this point in the thermal capacitance C_h, or leave by conduction through R_5. At the base plate, heat may again be stored in C_b or conducted to the cold plate through R_6. At the cold plate, both the steady state prelaunch condition and the postlaunch transient condition are taken care of by the switch S. Prior to launch, the switch is closed and heat will pass through R_7, contributing to the mean water temperature T_w. In this mode, the lumped thermal capacitance of the cold plate, which includes the local metal and water elements, will be at some temperature increment above the water temperature due to the temperature drop across that part of the overall cold-plate resistance which is included in R_7. At launch the constant temperature source is removed by opening

* A list of notation appears at the end of this chapter.

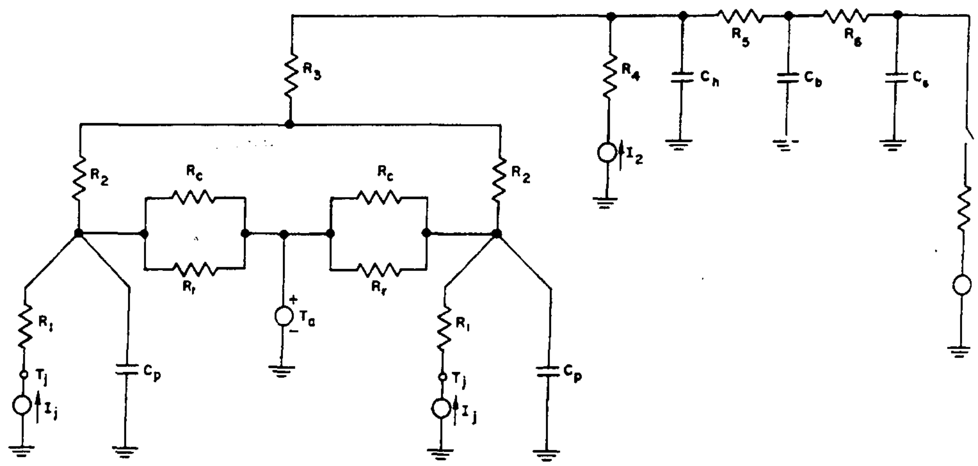


Fig. 2. Power amplifier thermal circuit.

the switch, but the thermal mass remains to absorb heat. The overall cold-plate resistance is split between R_6 and R_7 since in the postlaunch transient all of the heat does not have to pass all the way to the water to be stored.

Consideration of convection and radiation at the transistors and neglect of similar paths from the housing appeared reasonable since wiring and insulation typical of the weld-pak technique covered most of the housing surfaces. These elements blocked heat transfer without offering any appreciable heat-storage effectiveness.

The next step was to simplify the circuit by combining parallel and series elements where possible. In this case, the symmetry of the two transistors permitted the consolidation shown in Fig. 3. In this new circuit, the transistor heat source and capacitance is double the original value with the new R_2 added to the R_3 conduction resistance to form R_9. The other change made eliminated R_4 since it has no effect on the response at the power transistors.

In the steady state prelaunch condition, the total resistance of R_9, R_5, R_6, and R_7 will be the sum of the individual thermal resistances between the base of the transistors to the cooling water.

These individual resistances include:

1. Transistor-base to mica-insulator contact resistance
2. Conduction resistance through the mica-insulator
3. Mica-insulator to housing-contact resistance
4. Conduction resistance through the housing
5. Housing to base-plate contact resistance
6. Conduction resistance through the base-plate
7. Base-plate to cold-plate contact resistance
8. Overall conduction and convection resistance from the cold-plate upper surface to the cooling water.

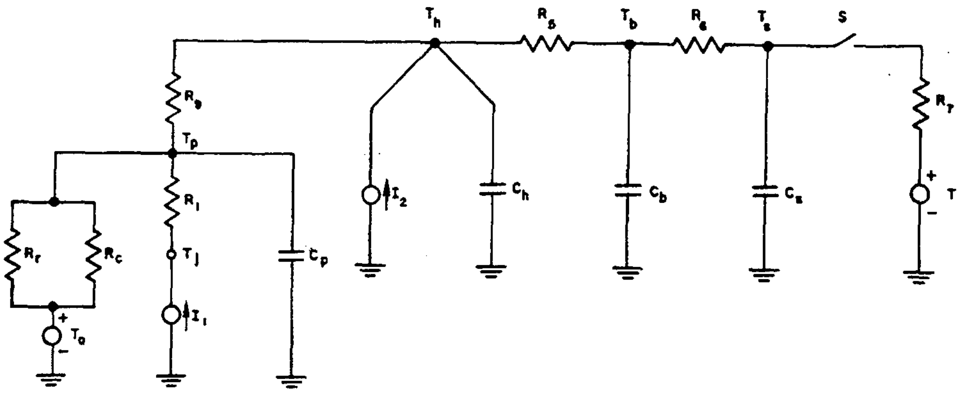


Fig. 3. Power amplifier thermal circuit (simplified).

The lumped capacitance of the housing C_h is a single lamina having thickness equal to the distance between the upper and lower surfaces at the location of the power transistors. This overall thickness could have been divided into more than one lamina; however, this would require shorter time increments in a numerical solution of the transient increasing machine calculation time and would have small effect on the overall accuracy of the solution due to the dominant effect of resistances other than conduction resistances[1].

For the purposes of this analysis, the housing capacitance was assumed to be at the midtemperature plane between the upper and lower surfaces. To accomplish this, the conduction resistance through the housing is split with half the resistance assigned to R_9 and half to R_5.

The base-plate capacitance C_b, is again a lamina of thickness equal to the element thickness. As in the case of the housing, the base-plate conduction resistance is split between the two adjacent resistances.

The cold-plate capacitance C_s, is a little more complex. The cold plate is a composite member of aluminum, stainless steel, and water with some specific overall resistance from upper surface to the cooling water. The magnitude of its capacitance is the sum of the capacitances of each of the constituent elements. For this analysis, it was assumed that all elements were at the midtemperature between the upper surface and the cooling water. This was accomplished in the thermal circuit during steady state by splitting the overall resistance of the cold plate between R_6 and R_7 and putting the switch S in the closed position. This charges the summed thermal capacitance of the element to the midtemperature prior to the switch being opened at launch.

With the problem in this form, the next step involves the determination of the values for the thermal circuit components. Since a digital computer difference equation solution technique is to be used, the component values may be constants, time-dependent functions, or temperature-dependent functions. Any consistent unit system may also be used. In this analysis, the Btu-hr-ft-°F set of units was used, but the w-in.-°C system could have been used just as well.

The constant-valued components in this circuit are the conduction resistances, capacitances, heat source I_2, and mean water temperature T_w. Each resistance was evaluated by summing all the thermal resistance between the adjacent points. For example, R_9 is a constant-valued conduction resistance and can be expressed as

$$R_9 = \frac{1}{h_d A_{pm}} + \frac{L_m}{k_m A_m} + \frac{1}{h_d A_{mh}} + \frac{L_h}{2k_h A_h} \tag{1}$$

As shown diagrammatically in Fig. 1, the heat conducted to the cold plate will flow through progressively larger areas. Within each metal element, an arithmetic average area was used in the conduction term in the applicable resistance equation. In the case of the cold plate, the value of the overall thermal resistance, given in terms of (°F-hr-ft^2/Btu), divided by the cold-plate effective area was split between R_6 and R_7.

Each capacitance is the product of the weight of the element and the specific heat for the material. In the case of the transistor capacitance, the actual transistor was weighed and a specific heat equal to that for copper assumed. The remaining constant value components were taken as specified. The dissipation of the power transistors I_1, was initially taken as a constant at the value shown in Fig. 1. A change in power dissipation with varying junction temperature was recognized but not evaluated. As indicated in the analytical result and a brief test program, this change of power with temperature had a large effect on the evaluation of the design.

The only time-dependent function appearing directly in the thermal circuit is the ambient compartment temperature T_a.

The convection resistance is both time- and temperature-dependent with the variation with time coming about due to a decrease in compartment pressure with time after launch. The R_c is then

$$R_c = \frac{1}{h_c A_p} \tag{2}$$

$$h_c = C\left[\left(\frac{k}{L}\right)\left(\frac{aL^3}{\Delta t}\right)^m\right]\left(\frac{P}{P_0}\right)^{0.5} \tag{3}$$

This equation was derived by combination of the basic free convection equation:

$$\mathrm{Nu} = C(\mathrm{Gr})^m(\mathrm{Pr})^n \tag{4}$$

where

$$\mathrm{Nu} = \frac{h_c L}{k} \tag{5}$$

$$\mathrm{Gr} = \frac{g\beta\Delta t L^3\rho^2}{\mu^2} \tag{6}$$

$$\mathrm{Pr} = \frac{C_p\mu}{k} \tag{7}$$

with the simplification

$$m = n = 0.25$$

and

$$a = \frac{g\beta\rho^2 C_p}{\mu k} \text{ (Free Convection Modulus)} \tag{8}$$

The $(P/P_0)^{0.5}$ term corrects the equation for use at any pressure with the remaining terms evaluated at a pressure of one atmosphere since ρ is the only term whose characteristics vary significantly with pressure. A linear variation of density with pressure is assumed and therefore the exponent of the pressure ratio term would be 2 if it were retained within the term raised to 0.25 power and is 0.5 if taken outside as shown.

The C and L terms of the equation are dependent upon the physical configuration of the surface. Values of $L = 0.5$ in. and $C = 0.61$ were used in this analysis to approximate the various possible attitudes of the assembly.

Values for the free convection modulus a and the air conductivity k were chosen based on a film air temperature of 145°F, an average value approximating conditions of the transistor's outer surface temperature and ambient temperature before and after launch. This permitted fixed-valued assumptions for a and k.

There are two sources of error in assuming constant values for these parameters. These are the lack of variation of both parameters with the change in film temperature that will occur and the lack of variation in a as P decreases during the flight. The changes in film temperature produce little effect since the product, $k(a)^{0.25}$ varies slightly with changes in temperature at constant g. The error due to changing g is also not too large since g appears only in the term which is raised to 0.25 power.

The radiation resistance is the temperature difference between the adjacent points divided by the heat flow due to radiation. Since the surrounding walls are large compared to the exposed area of the two transistors, the emissivity and view factors simplify to the point that the radiation resistance can be expressed as

$$R_r = \frac{T_p - T_a}{\delta A_p \epsilon_p [(T_p + 460)^4 - (T_a + 460)^4]} \tag{9}$$

This radiation resistance may be replaced by a heat source with a magnitude equal to the denominator. This simplifies the circuit element necessary to define the radiation heat transfer but is sometimes confusing in that it is a heat source that does not add heat to the system, but merely defines the heat flow in that path.

At the equilibrium condition with the switch in the closed position, the transistor can temperature is determined by a trial-and-error evaluation. In this problem, convergence occurs very quickly since the impedance of the convection and radiation paths is very high compared to the conduction path. After this temperature is determined, all remaining nodal temperatures can be determined directly by evaluating the IR thermal gradients between nodes, thus giving a full set of initial conditions for the transient condition.

The transient analysis to compute the temperatures at the various points in the assembly involved writing the heat balance equations at each nodal point in the circuit. The heat flow through a resistance element was based on the potential or temperature difference existing at the start of each time increment, $\Delta\theta$, while the heat flow into a capacitive element was based on the temperature rise or change in capacitor charge from the start to the end of the time increment. In addition, the values for R_c and R_r were recalculated through the entire transient based on the calculated transistor package temperature T_p at the start of each time increment and the values of air temperature and pressure applicable at the start of the particular time increment.

In detail, the computation went through the following steps:

a. *Re-evaluation of R_c and R_r* using the initial condition values of T_p, T_a, and P, using the equations described earlier.

b. *Heat balance at nodal point p.* Summing the heat flows at this point, we get

$$I_1 - \frac{T_p - T_a}{R_c} - \frac{T_p - T_a}{R_r} = \frac{c_p(T_p' - T_p)}{\Delta\theta} + \frac{T_p - T_h}{R_9} \tag{10}$$

where T_p' is the temperature at point p after $\Delta\theta$ seconds. This equation may then be solved for the single unknown T_p'.

c. *Heat balance at nodal point h.* Summing the heat flow at this point, we get

$$\frac{T_p - T_h}{R_9} + I_2 = \frac{C_h(T_h' - T_h)}{\Delta\theta} + \frac{T_h - T_b}{R_5} \tag{11}$$

Here T_h', the unknown temperature at point h after $\Delta\theta$ seconds may be determined.

d. *Heat balance at nodal point b.* Summing the heat flows at this point, we get

$$\frac{T_h - T_b}{R_5} = \frac{C_b(T_b' - T_b)}{\Delta\theta} + \frac{T_b - T_s}{R_6} \tag{12}$$

e. *Heat balance at nodal point s.* Summing the heat flows at this point, we get

$$\frac{T_b - T_s}{R_6} = \frac{C_s(T_s' - T_s)}{\Delta\theta} \tag{13}$$

Here, the unknown T_s' may be determined.

All nodal temperatures at the end of $\Delta\theta$ seconds have now been determined. These values now become the initial conditions applicable to the succeeding $\Delta\theta$ time increment, and the steps above are repeated.

f. *Determination of T_j.* Since the junction of the transistor has negligible heat-storage capability for this type of transient, its temperature follows the case temperature without any lag and can be expressed as

$$T_j = T_p' + I_1 R_1 \tag{14}$$

The remaining item to be chosen is the size of the time increment. As explained in [1], variation in the magnitude of $\Delta\theta$ will affect the accuracy of the results.

Large time increments cause excessive storage since the magnitude of the heat input does not decrease during the time increment as the capacitor charge increases and, likewise, the heat flow away does not decrease. In the extreme case, this will lead to oscillations where the capacitor charge will increase to a temperature higher than the temperature of the point from which the heat is coming. As the time increment is made smaller, the error in temperature due to the $\Delta\theta$ magnitude will decrease as curve-smoothing takes place. In this analysis, test computer cases were run with $\Delta\theta = 2$ sec, 1 sec, and 0.5 sec, and at $\theta = 90$ sec for a reference point, the variation in junction temperature between the 0.5- and 1.0-sec computation was 0.47°F and between 1.0- and 2.0-sec computation, the variation was 0.95°F. This indicates a variation of less then 2.0°F between a 2-sec time increment computation and an infinitesimal tile increment, since the variation is approximately halved for a halving of the time increment:

$$\sum 0.95 + \frac{0.95}{2} + \frac{0.95}{4} + \cdots + \frac{0.95}{2n} < 2.0$$

Owing to the reduction in machine calculation time required with larger time increments, a probable error of 2.0°F due to choice of $\Delta\theta$ was accepted and all subsequent calculations were made with $\Delta\theta = 2.0$ sec. This technique of evaluating the effect of changing $\Delta\theta$ by trial computations is a practical method when a high-speed computer is available.

The time–temperature histories were determined for combinations of possible conduction resistance and ambient conditions, to indicate the range of transistor junction temperature, degree of influence of specific parameters, and typical temperature distributions within the assembly. The principal variables were the magnitude of the transistor internal resistance, the contact resistance at the various joints, and the ambient conditions. The specific results were shown as plots of temperature *vs* time. Two of these temperature histories are shown in Figs. 4 and 5 to indicate the "best estimate" for the missile compartment and laboratory bench environments.

Since the rise in junction temperature was appreciable, a test model with just the two power transistors was assembled and tested. The measured equilibrium temperatures compared fairly well with the analytical. A full transient test run was not possible since the overload protection on the amplifier input interrupted the test. This interruption was probably due to a runaway condition of increasing transistor power dissipation with temperature. Fortunately, a similar circuit using silicon transistors was under development and its substitution gave increased stability and higher permissible component temperatures. However, subsequent analysis of the dissipation *vs* junction temperature for the 3N50 in this particular circuit took into account the variation of saturation or reverse current with temperature. The resulting definition of power dissipation is shown in Fig. 6. When the thermal circuit I_1 is varied according to this curve by taking on a magnitude applicable for the junction temperature at the beginning of each $\Delta\theta$ time increment, the predicted temperature histories became as shown in Fig. 7. Here,

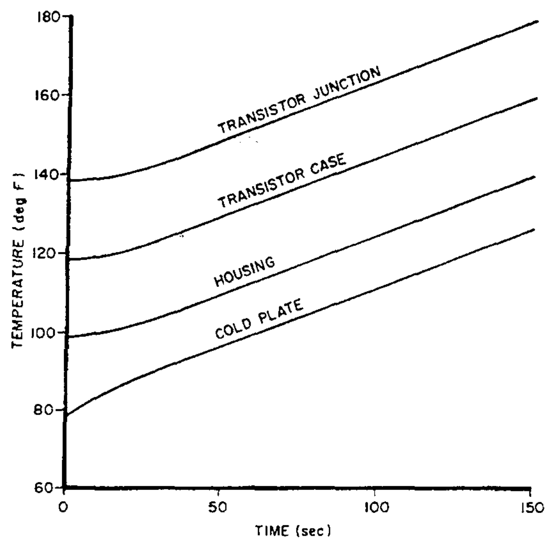


Fig. 4. Power amplifier post-launch temperatures missile compartment conditions.

the calculated junction temperature exceeds the absolute maximum rating of 212°F (100°C) within the time period of concern.

The preceding example was chosen for discussion here since it includes radiation, convection and conduction with both time- and temperature-dependent elements. These characteristics illustrate the necessity of some shorthand representation such as the *RC* thermal circuit for the thermal problem, and the method of difference equation solution. Unfortunately, the amount of test data on

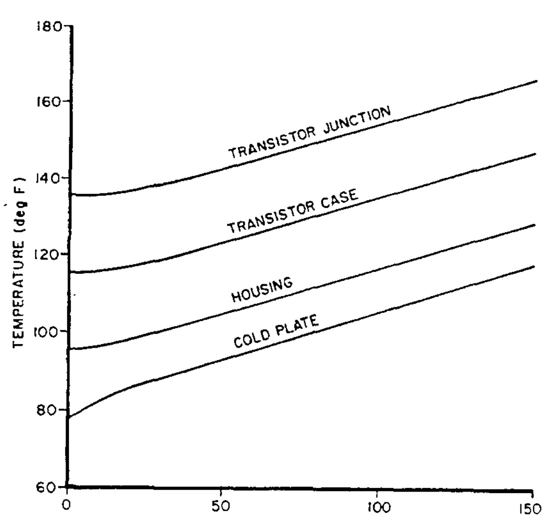


Fig. 5. Power amplifier post-launch temperatures laboratory conditions ($I_2 = 0$).

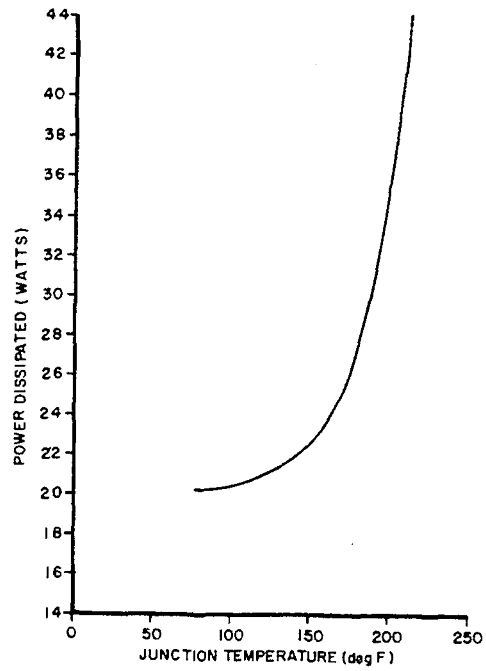


Fig. 6. Power amplifier 3N50 transistor power dissipated as a function of junction temperature.

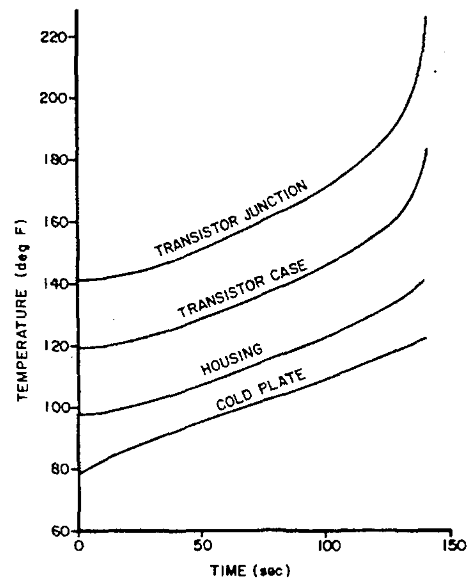


Fig. 7. Power amplifier post-launch temperatures, laboratory conditions, transistor power varying with temperature.

the sample package is extremely limited since the product improvement involved extensive circuit changes which both increased the thermal stability and the permissible upper temperature limits. The test program on the new configuration was also limited since the thermal problem was greatly reduced.

DISCUSSION

When the thermal properties of an assembly are represented by an analog thermal circuit, each of the characteristics of heat transfer or heat storage is treated alone. This simplifies the problem but also introduces errors in the solution due to gradients within the heat-storage elements. These errors, while not evaluated here, are minimized when there is significant thermal resistance between heat storage elements, as in the case where contact resistance is considered and the metal heat-storage elements have high thermal conductivity and short heat flow paths. If the metal elements have to be broken into laminae with the total heat storage capacity distributed among several circuit capacitances with connecting incremental thermal resistances, specific attention should be paid to choosing the time increment $\Delta\theta$ small enough so that stability and reasonable accuracy is maintained. This is accomplished in simple cases by choosing $\Delta\theta$ equal to or less than one-half the local time constant. For example, if the response of the central member of a composite slab consisting of a metal element with insulation on each side, is desired, the analog thermal circuit would be as shown in Fig. 8.

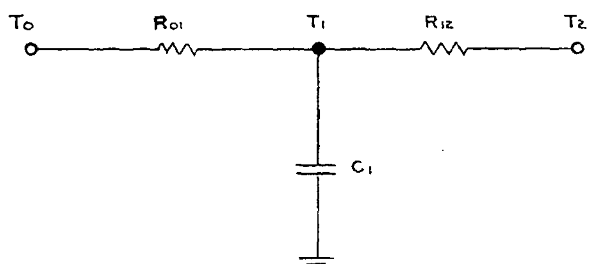


Fig. 8

and the exact expression for T_1 as a function of time, assuming a zero initial T_1, is

$$T_1 = \frac{R_{01}T_2 + R_{12}T_0}{R_{01} + R_{12}}\left[1 - \exp\left(\frac{\theta}{R_{01}R_{12}C/R_{01} + R_{12}}\right)\right] \tag{15}$$

and the time constant τ is

$$\tau = \frac{R_{01}R_{12}C}{R_{01} + R_{12}} \tag{16}$$

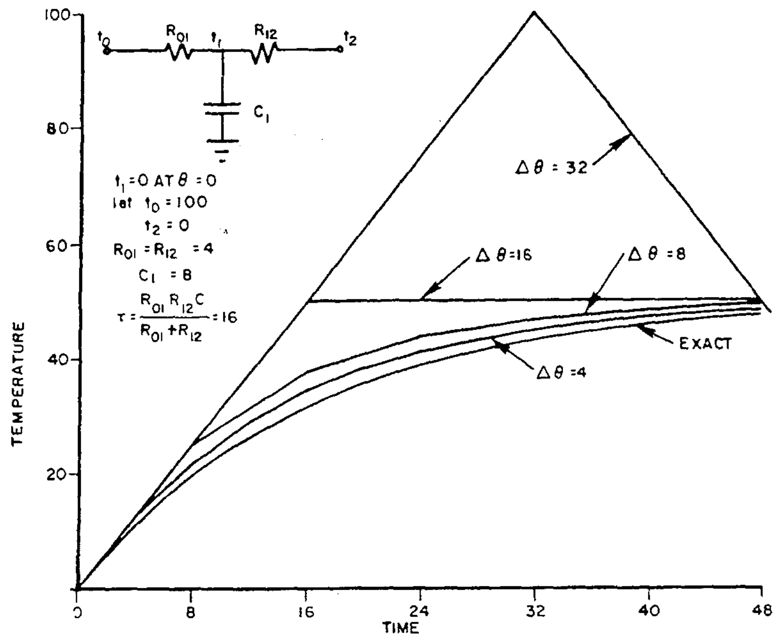


Fig. 9. Metal temperature in a composite slab.

The effect of varying $\Delta\theta$ is shown graphically in Fig. 9 for a numerical case:

$$T_0 = 100 \qquad R_{01} = R_{12} = 4$$
$$T_2 = 0 \qquad C_1 = 8$$
$$T_1 = 0 \quad \text{at} \quad \theta = 0$$

The curves include the exact solution of the applicable differential equation and the difference equation solution for various values of $\Delta\theta$.

In more complex circuits, the exact solution for temperature at a point includes exponential terms with different time constants. However, good results are usually obtained by choosing a $\Delta\theta$ equal to one-half the smallest local time constant, and testing for the accuracy of the difference equation solution by running several test calculations with smaller values of $\Delta\theta$. The relationship of $\Delta\theta$ to the time constant can also be used in forming the analog thermal circuit. If local time constants are evaluated approximately as the circuit is being prepared, those sections with small time constants can be lumped with adjacent elements or those sections with large time constants can be further divided. This relationship of accuracy to $\Delta\theta$ and time constant is applicable only in the passive portions of the circuit. If time-dependent elements vary radically with time, smaller time increments are obviously necessary.

In summary, thermal transients in complex assemblies can be evaluated easily with the shorthand of the analog thermal circuit and the flexibility of the digital computer to solve the difference equations.

The results of this technique will never duplicate the exact phenomenon, but will be adequate for engineering evaluation of designs before models are fabricated for test and where duplication of combined environment transients is impossible.

NOTATION—GENERAL

A = Area, ft^2
C = Thermal capacitance, Btu/°F
I = Heat source, Btu/hr
L = Length, ft
P = Pressure, psia
R = Thermal resistance, °F-hr/Btu
S = Switch
e = Base of Naperian logarithms
h = Unit conductance, Btu/hr-ft^2-°F
k = Thermal conductivity, Btu-ft/hr-ft^2-°F
T = Temperature, °F
θ = Time, sec
τ = Time constant, sec

Subscripts
1, 2, 3 = Points in thermal circuit
a = Ambient
b = Base plate
c = Convection
d = Contact
h = Housing
j = 3N50 transistor junction
m = Mica
0 = Standard conditions
p = 3N50 transistor package
r = Radiation
s = Cold plate
w = Cooling water

NOTATION—RADIATION AND CONVECTION

(The following notation is used only in the computation of equivalent radiation and convection resistances.)
δ = Stefan–Boltzmann constant
ϵ = Emissivity
C = Shape factor—free convection

L = Significant length dimension, ft
k = Thermal conductivity of the fluid, Btu-ft/hr-ft^2-°F
P_0 = Atmospheric pressure = 14.7 psia
g = Gravity constant, ft/hr^2
β = Coefficient of thermal expansion, ft^3/ft^3-°F
ρ = Density, lb/ft^3
μ = Viscosity, lb/ft-hr
c_p = Specific heat at constant pressure, Btu/lb°F
Δt = Temperature difference between surface and fluid, °F
Nu = Nusselt number
Gr = Grashof number
Pr = Prandtl number
m, n = Exponents in the general convection equation

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DISCUSSION

Q. (Harry Baker, Philco Corporation, Palo Alto, Calif.) Was the milled heat sink block that you showed strictly for a laboratory test?

A. No. That block is typical of those being used in completed assemblies.

Q. For flight hardware?

A. Yes.

Q. What was this circuit? Was this a high-frequency amplifier?

A. No. This is a low-frequency power amplifier.

Q. (John Meyer, Sylvania Electric, Williamsville, N.Y.) I am interested in the types of capacitors you used in your analog. Do you know what type they were and what type of leakage resistance they had? I have done some work with this kind of circuit before and I am interested to see what problems you ran into with your capacitor.

A. Perhaps this is one point which wasn't adequately covered. The thermal analog circuit is not used to duplicate heat transfer electrically, but is used as a shorthand representation of a thermal system. I am not building circuits to see temperature *vs* time on a scope. I just cannot draw the picture of all these heat transfer modes and energy storage effects and keep track of them without the tool of the shorthand of the circuit.

Q. (B. Edney, Minneapolis-Honeywell, Seattle, Wash.) In your heat sink with the little drilled cavities for mounting the resistors and transistors, were the components bonded in place and, if so, with what material?

A. Different techniques were used. In most cases, the epoxies were quite adequate. In other cases, where small transistors had large tolerances on can diameter, other techniques had to be used to reduce the thermal gradient through the bonding material.

Q. (Martin Camen, Bendix Corporation, Teterboro, N.J.) Have you done any work with thermoelectric coolers as opposed to the milled, honeycomb metal casting?

A. We have been looking for practical applications for thermoelectrics in electronic packages for several years and have not found one yet.

Q. Wouldn't this be an application possibly to reduce the weight that is added when you go into these structural devices?

A. As a general rule, if the system design permits running the heat dissipating items at a temperature higher than the sink, the least weight cooling design will be achieved by short paths through high-conductivity materials. The particular assembly discussed here is part of a much larger system designed for water cooling with relatively cool water. Since this sets the sink temperature at a low level, the simple conduction design is the most practical.

Q. (George Snyder, HRB Singer, State College, Pa.) After you ran your computer analysis, did you get a chance to check your answers with some actual temperatures as you encountered them. If so, how close did it come out?

A. Yes we did, although the test work was limited in the rush to get a finished product ready to go. There was vast deviation between what was initially calculated and what was measured in the lab. Most of this was caused by a temperature-dependent power dissipation condition. The initial calculations were based on a fixed dissipation. Not even normal engineering accuracy is possible when the given information is inaccurate.

Q. Did you go any further with the mathematics to correlate numerical or relaxation methods with the computer method? In other words, with further problem simplification, could you get an answer reasonably close to your computer solution?

A. Closed-form solutions for the actual assembly would have been extremely complex and were not attempted. However, comparisons of various solutions were made for simple configurations, such as the numerical example shown in the last figure. The closed-form solution of the midplane temperature, as given in Carslaw and Jaeger or Jakob, does not come any closer to the "exact" solution than the marching solution with a $\Delta\theta$ of one-half the time constant.

Q. (A. V. Painter, Bendix Computer, Los Angeles, Calif.) Your matrix seemed to be an anodized aluminum block, while your heat sinks seemed to be iridited. What contact coefficient for these did you use?

A. Solutions were obtained for various values. The one presented here was for a conservative estimate of 2000 Btu/hr-ft^2-°F.

Packaging of Electronic Systems Utilizing Commercially Available Integrated Circuits

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Raytheon Company, Bedford, Massachusetts

An advanced packaging group has been in operation for the past year at Raytheon Company, Missile and Space Division. This company-sponsored program was originated specifically for the purpose of study and design of packaging concepts which utilized the latest practical developments in the electronic-component field.

ONE PHASE of the advanced packaging program at Raytheon involved using commercially available integrated circuits as applied to the construction of digital systems. The concepts developed, although not tied to any specific task or program, would envision use of these units with regard to variation of size and form factor. The task presented was to take a representative digital circuit and package it using various types of integrated circuits. A six-bit binary counter was selected as being a typical digital application. A comparison could then be made of problems encountered with the design and producibility of several systems, each utilizing a different component configuration.

Most commercially available integrated circuits are an assembly of many circuit, or equivalent circuit, elements located inside a microminiature device. Internal element interconnections are constructed using a variety of techniques. Multiple leads extend from the unit for system integration. One of the main advantages of this type of device is the ability of the system engineer to pretest a circuit function before adding the unit into a system. System reliability will increase because element interconnections can be considered as virtually eliminated. However, the problem still remains for the external system interconnection of these devices and the reliability of these connections.

The design of a basic module is the most important problem associated with utilizing integrated circuits in a digital application. The correct design of this basic module will permit large complex digital systems to be reduced to smaller repetitive subassemblies. These subassemblies will be considered as throwaway types since they will be extremely difficult to repair. Since this unit is considered expendable, the size and design of the unit will be determined primarily by the cost. Another determining factor for module size is the grouping of related circuits to minimize required module to module interconnections. The larger the basic module, the fewer the required interconnections from it to the rest of the system. Thus, the final size becomes a trade-off between the reduction of system interconnections and the increased cost of the integrated circuits contained in the throw-away unit.

Integrated circuits are produced in different form factors ranging from a flat rectangular package to a variety of JETEC transistor case sizes. For this reason, the following configurations were chosen:

> Texas Instruments "Solid Circuits," with a flat rectangular form factor; Fairchild Semiconductor Corp., Micrologic, constructed in a TO-47 case with an eight-pin header; and Raytheon Company Integrated Circuits in a compressed TO-5 case with a ten-pin header. In utilizing these devices, the principal problem experienced by the system packaging engineer is interconnection. This problem is twofold. Difficulties are realized in making interconnections between the units; also further complication results from having multilead miniature devices whose leads project into a very limited area of a printed circuit board. With these units, the final assembly size reduction is limited by the interconnection pattern of the leads on the printed circuit board, rather than by the size and proximity of the devices. In order to get adequate spacing between lands of adjacent component leads, while maintaining minimum spacing between individual units, special interconnection patterns had to be devised.

Figure 1 is a schematic of a six-bit binary counter composed of six interconnected Raytheon flip-flops. The input is fed into Pins 4 and 8 of Stage I. The output, Pins 5 and 10 of Stage I, is connected to Pins 4 and 8 of Stage II. The output of each stage drives the unit in the following stage until the final output is picked off Pins 5 and 10 of Stage VI. Each stage output is monitored separately. In each stage Pins 2 and 7 are tied together and monitored. Pins 3 and 9 of each unit are individually brought out to ground. All number 1 pins are connected to $+6$ v; -3 v is tied to all number 6 pins.

Illustrated in Fig. 2 are the component parts that make up the modular assembly plus the subassembly of the integrated circuits on an individual panel board. The integrated circuit is packaged in a compressed TO-5 case with a ten-pin header. Two printed circuit panel boards are required for each module. These boards have printed patterns on both sides. All small holes are plated-through. Note that the areas on both sides of the board beneath the component device are utilized for interconnection purposes. Large clearance holes in the boards permit the intermeshing of the subassemblies for maximum use of the volume. Since all holes are throughplated, soldered interconnections can be performed from one side of the board. The subassembly located on the top of the illustration shows the devices assembled and soldered in place.

Figure 3 demonstrates the final assembly of the counter prior to embedding. At this stage of assembly the unit is electrically tested. Repair of the assembly can be accomplished before embedment.

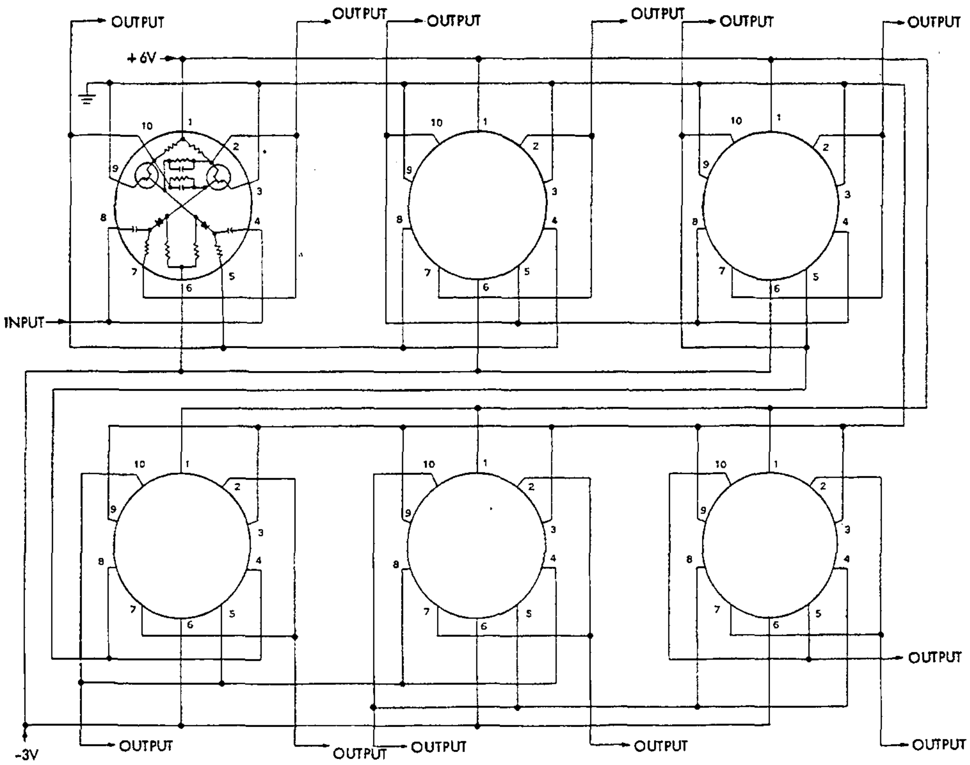

Fig. 1. Raytheon six-bit binary counter—schematic.

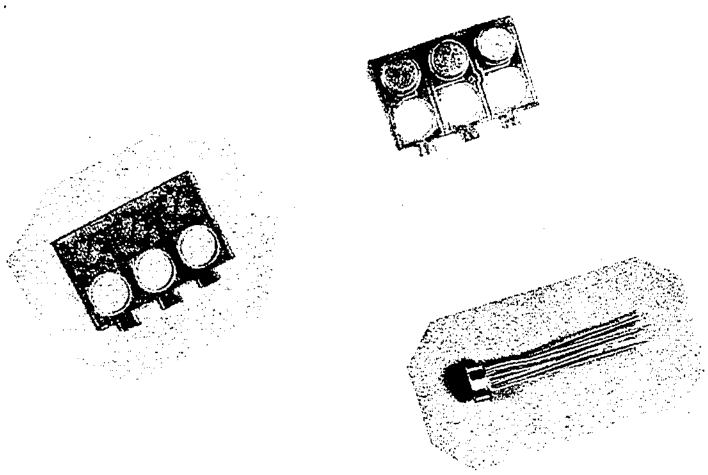

Fig. 2. Raytheon integrated circuits—subassembly.

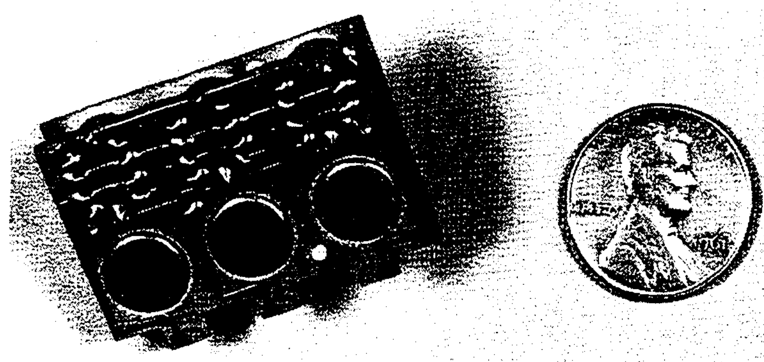

Fig. 3. Raytheon assembly prior to embedment.

This type of construction gives more rigidity to the assembly and allows it to be of a thinner cross section. The connections between boards are made by soldering buss wire between plated-through holes on the two boards.

The completed unit (Fig. 4) has the serrated edges of the panel boards protruding from the plastic. These feet will be soldered to a notched printed circuit parent board for system integration. In order to restrain the modules, mechanical retention devices may be used to supplement the electrical contacts. Straps or retaining plates are two possible approaches to this problem. The mechanical device may also provide a means of conductive cooling for the embedded units.

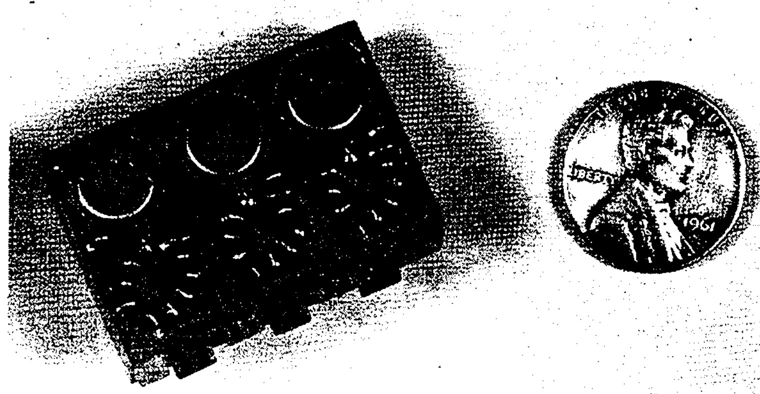

Fig. 4. Raytheon embedded assembly.

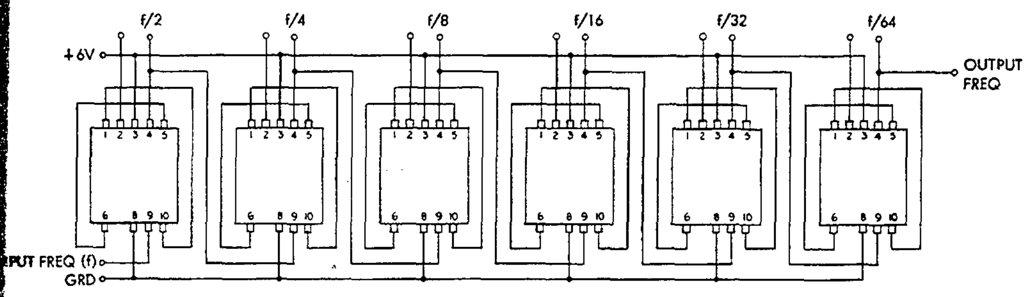

Fig. 5. Texas Instrument six-bit binary counter—schematic.

Thus the use of mechanical restraining devices in the system would accomplish a joint purpose.

The final module assembly with the dimensions of $1\frac{3}{8}$ long by $\frac{7}{8}$ high by $\frac{5}{16}$ thick has a volume of 0.375 in.^{3}. This unit contains the equivalent of 16 circuit elements per can, or 96 elements in the 0.375 in.^{3}. The packaging density obtained is approximately 442,000 parts/ft^3.

The second unit to be described is a six-bit binary counter utilizing Texas Instrument Solid Circuits. These devices have a flat rectangular form factor. The assembly uses a soldered type of construction employing printed circuit boards.

Figure 5 shows a schematic diagram of the T.I. assembly. Two pairs of diagonally opposed pins are jumpered per unit, 5 and 6, and 1 and 10. The input is fed into Pin 9 of Stage I. Pin 4, the output of each stage, connects to Pin 9 of the following stage; +6 v is tied to all number 3 pins. All pins number 8 are brought out to ground. Monitoring of individual stages is brought out on pins numbered 2.

The component parts and the subassembly of the interconnecting pad are shown in Fig. 6. The two large objects are printed circuit parent boards. The smaller

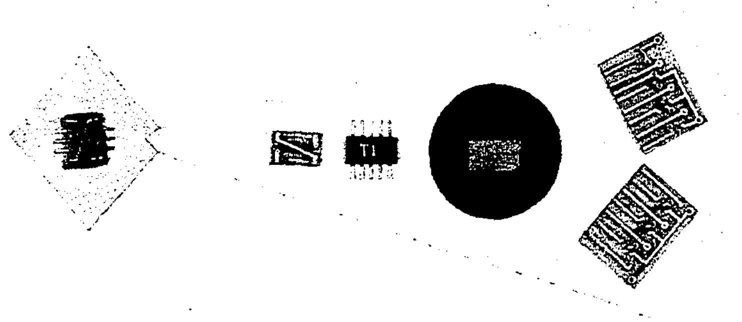

Fig. 6. Texas Instrument solid circuit subassembly.

unit is an interconnection pad which provides circuit integrity for the diagonally opposed pins of the device. Plated-through holes are used in order to provide electrical continuity through the boards. An insulating pad is also used to separate the stages and the interconnecting pad from the device. Located at the top on the left is one stage subassembly composed of an interconnecting pad, an insulating pad, and flip-flop device.

Figure 7 depicts the final assembly of the unit prior to embedment. The leads of the subassemblies project through the boards and are soldered in place. The remaining required interconnections between the two parent boards are performed by buss wires which are soldered between the throughplated holes. After electrical test the unit is ready for embedment.

Figure 8 shows the embedded unit in its final assembly. The two main boards project from the plastic into a printed circuit parent board. As mentioned in the previous system, consideration will be given to employing a device for mechanical retention and conductive cooling. The outside dimensions of the cast assembly containing a volume of 0.0384 in.^{3} are 0.515 long by 0.281 high by 0.265 wide. Although 31 component areas are possible in the T.I. device, only 16 of them are used in this application. Since there are six devices used per assembly, the unit contains the equivalent of 96 circuit elements. Thus, the packaging density of the unit, having a volume of 0.0384 in.^{3} and containing the equivalent of 96 circuit elements, is 4,320,000 parts/ft^3.

The final assembly to be discussed is the six-bit binary counter utilizing Fairchild Semiconductor "Micrologic." Fairchild's units are contained in TO-47 JETEC cases having eight-pin multilead headers.

The schematic using Fairchild Micrologic, is shown in Fig. 9. Each stage is composed of one counter adapter and 2 half-shift registers or a total of 3

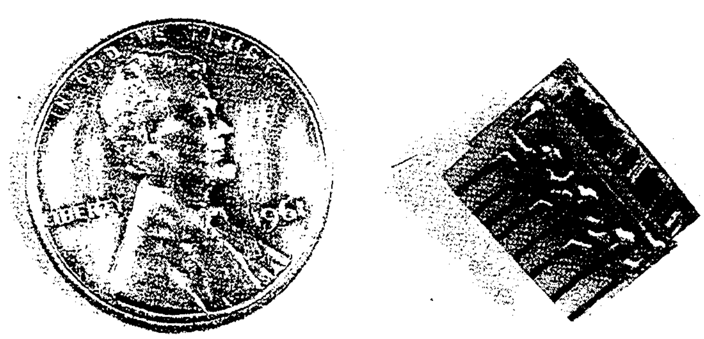

Fig. 7. Texas Instrument assembly prior to embedment.

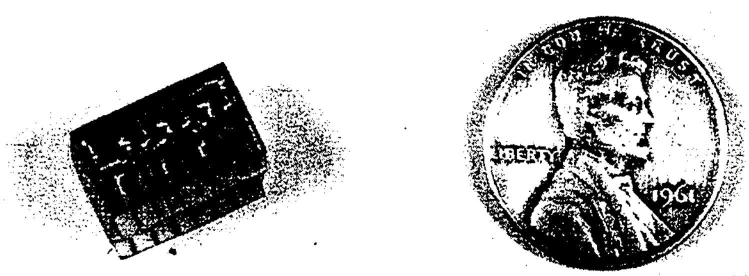

Fig. 8. Texas Instrument embedded assembly.

Micrologic cans per stage. The total counter is composed of 6 counter adapters and 12 half-shift registers or a total of 18 units for the complete assembly.

It will be noted the interconnection problem on this unit is more complex in relation to the other two units. Not only must connections be devised between stages, but continuity between devices in each stage must be maintained. Shown on the schematic are individual leads which monitor the signal between the counter adapters of each stage. Due to the large number of Micrologic units contained in the system the packaging engineer's problem of interconnections is quite formidable.

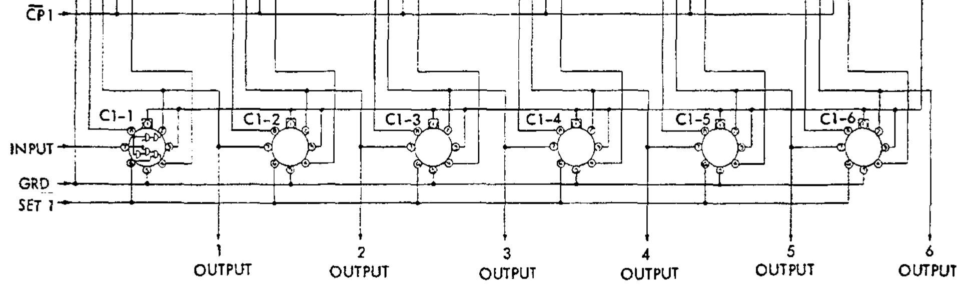

Fig. 9. Fairchild six-bit binary counter—schematic.

Figure 10 illustrates the required component parts which are used to construct the subassembly shown at the top on the right.

The devices assembled to the board have the deceptive appearance of being sparsely separated. This is not true. The spacing between the units is governed not only by the interconnections that can be seen, but also by the intermeshing devices mounted to the opposing panel board. Interconnections are made by use of two printed circuit boards utilizing plated-through holes. These holes provide not only the means of mounting the integrated circuits, but they also accomplish circuit continuity by allowing the use of buss wire for interconnections between the two panel boards. The holes have the added feature of providing continuity through the board. In this manner all soldered connections can be performed from one side of the board. Since the pin spacing on the TO-47 cans prevents the lands on the printed circuit board from having an adequate isolation space, a land pattern for staggered pin connections was devised. The alternate leads which bend outward will have their bolt circle centerline spacing approximately equal to the diameter of the TO-47 case.

The completed subassemblies are shown in Fig. 11.

Spacing between the units is determined by the number of interconnecting leads that have to pass between the devised land patterns. This spacing may be decreased by the use of multilayered printed circuit boards which superimpose certain conductive patterns. The superimposed patterns are stacked on alternate layers of the boards. For ultimate use of packaging volume the devices of one board nest between the units on the opposing board. The tops of the cases on the first board pass over the interconnecting paths of the opposing board.

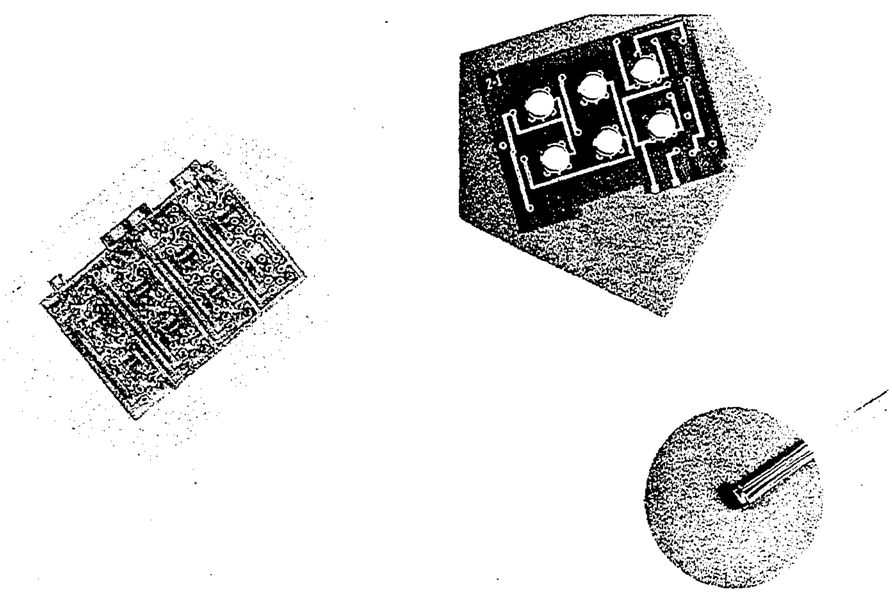

Fig. 10. Fairchild micrologic subassembly.

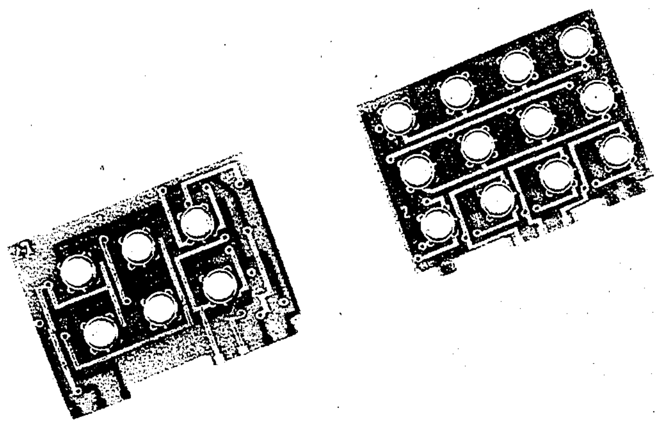

Fig. 11. Fairchild subassemblies—forward and reverse.

The required volume for the assembly is utilized more efficiently because the nesting principle makes partial use of the overhead volume of the interconnection paths. Serrations at one edge of each board permit terminations of the module and provide continuity with the printed circuit parent board. As previously mentioned in the other assemblies a mechanical means of retention and cooling will be considered for system integration. Figure 12 depicts the final assembly prior to embedment. The interconnecting buss wires provide not only module continuity, but mechanical rigidity to the assembly as well. The unit is then electrically tested before embedment.

The embedded assembly (Fig. 13) has the dimensions of $1\frac{29}{32}$ long by $1\frac{9}{32}$ high by $\frac{9}{32}$ wide and contains a volume of 0.686 in.^{3}. Each half-shift register contains 14 equivalent circuit elements per unit while the counter adapter contains 13 equivalent circuit elements per unit. There are 41 elements per stage or a total of 246 elements per six-bit binary counter. The packaging density attained in this assembly is 620,000 parts/ft^3.

Since the three assemblies have been constructed to the same basic digital system, it is possible to compare the volumetric efficiency of the packaging techniques utilizing the different form factors of the devices as a criterion. Reverting back to the Raytheon module, the volume of the embedded assembly is 0.375 in.^{3}. This volume is calculated using the outside dimensions of the embedment material. The volume of the contained parts totaled 0.1864 in.^{3}. The packaging efficiency of the module using integrated circuits contained in the compressed JETEC TO-5 cases is 49.8% of the overall embedment volume.

As mentioned previously the volume of the embedded T.I. assembly is 0.0384 in.^{3}. The total components volume is 0.01531 in.^{3}. The packaging efficiency of the module is 40.0%. This is the comparison between the overall volume of the embedded assembly and the actual volume occupied by the component devices and component parts. Although the packaging efficiency of this assembly seems low, it must be remembered that due to the extremely small size of the module any amount of embedment material will drastically affect the packaging efficiency of the unit.

The final type of module to be discussed is the assembly utilizing the Fairchild Semiconductor Corporation Micrologic. The component parts of the Fairchild assembly occupy a volume of 0.2357 in.^{3}. The cast unit, measured to the extreme dimensions of the casting material, occupies a volume of 0.686 in.^{3}. The calculated packaging efficiency of the unit is 34.4%.

Although the above facts and figures tend to prove that the parts contained per cubic foot reach astronomical figures, the figures as shown apply only to the parts density of the module. For system integration where interconnecting parent boards, connectors, and heat transfer devices in addition to case and support structure are required; the parts density for the system will be considerably less. The type of information that can be ascertained as having some value is the volumetric efficiency that is possible in utilizing the different unit configurations for the product design of a system.

In summary, the main design problem encountered in utilizing the JETEC configuration integrated devices is the lack of printed circuit land area available in

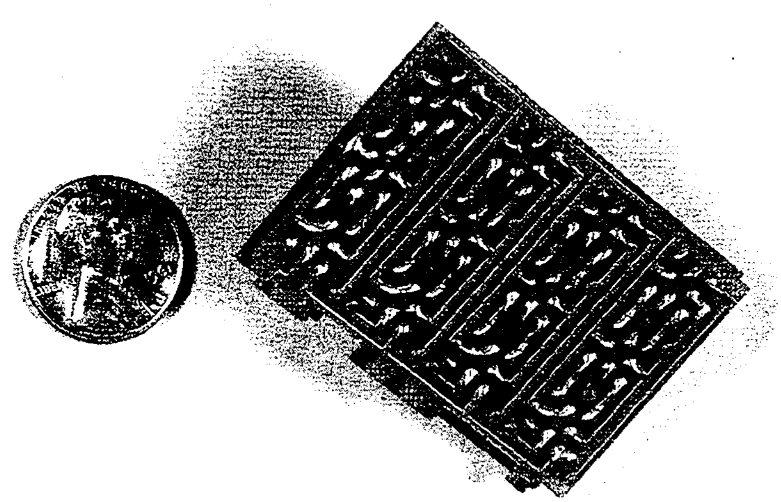

Fig. 12. Fairchild assembly prior to embedment.

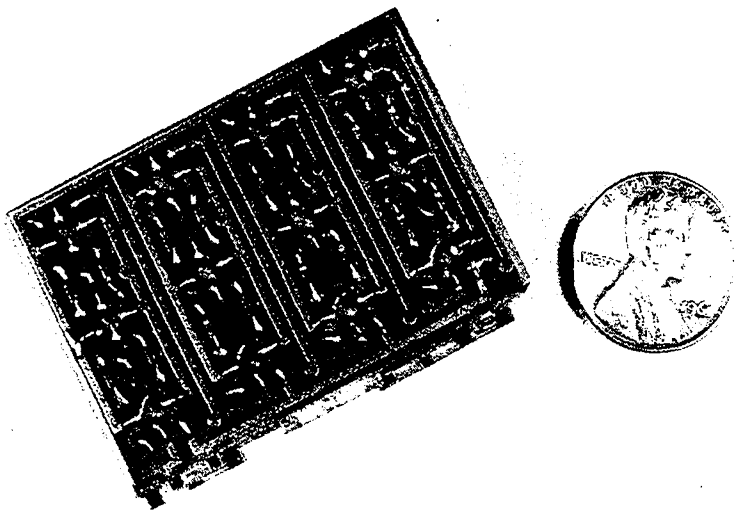

Fig. 13. Fairchild embedded assembly.

immediate proximity to the device. Landless plated-through holes may be a solution to this problem. The Texas Instrument devices, because of their size, make construction of modules using a production soldering technique extremely difficult.

The previously mentioned systems, packaged as shown, are not an attempt to show the concepts as a final solution, but they do represent an attempt to illustrate possible solutions to design of systems employing integrated circuits. Since there was no specific application in mind, the final modular form factor was arbitrarily chosen.

DISCUSSION

Q. (Dick Anderson, Fairchild Defense Products, Palo Alto, Calif.) I think it should be noted that in the "micrologic" assembly you have included enough logic to build a parallel fast-carry counter which is logically more powerful than the others. To build the equivalent ripple through a six-stage counter would require $\frac{1}{3}$ fewer micrologic cans than you used here.

A. When this program was started, I referred to a circuit that was recommended in your micrologic handbook.

Q. All right, I can appreciate that. Probably in the handbook at the time you started this project that was the best thing you had to go on. Since then applications information has been published which shows you how to cut the required units down by $\frac{1}{3}$.

A. Prior to this moment, I was operating under the assumption that I had the latest information.

Q. (Bill Diangson, Philco Corporation, Palo Alto, Calif.) Do you have a throwaway cost figure on your T.I. modules?

A. At this time, approximately \$260. At present, the cost of the 6 T.I. units is \$240. The remaining components and final assembly cost totals \$20. The cost of the completed assembly is \$260.00. This figure will decrease with the reduction in cost of the T.I. units.

Q. One other question. Did you have difficulty in bending the T.I. unit's leads? This is in reference to the breaking of these leads by bending or handling.

A. No difficulty was experienced in this respect as long as reasonable caution was used. I assembled the module at my desk in the space of one morning.

Q. (Lou Polaski, General Electric, Valley Forge, Pa.) You mentioned that you were primarily interested in form factors for a packaging concept with no particular application in mind. You also mention that you have thought about ways of thermal dissipation, and as I recall some of the Fairchild micrologic components can dissipate as much as 70 and 80 mw. This is quite a bit when you only have a conductive heat sink in an aerospace application—have you gone into packaging for thermal dissipation by conduction? It doesn't seem that the packaging configuration that you came up with really took this into too much consideration.

A. No. I have not gone into the mathematical analysis of the heat dissipation at this time. But I do have a method to accomplish this. What I have in mind would be to place a metal plate between the two panel boards. The plate would be in contact with the cases of the individual units. The edges of the plate would protrude from the encapsulated unit in order to be in contact with a common heat sink.

Q. Are these cans electrically hot?

A. No.

Q. They are ground, did I hear the Fairchild man say? This would present a problem with cases where the case, which is the ultimate heat sink, is electrically hot.

A. This is true. The solution for the preceding problem would not always be applicable. The problem of thermal dissipation would have to be considered and the solution presented in each specific application.

Q. (Bob Clenner, Philco Corporation, Palo Alto, Calif.) Are the T.I. devices in their original concept or is this the new low-power type?

A. The study was started a year ago and we used the original design concept.

Q. Do you know the power dissipation of the completed module?

A. No, I do not.

Q. (Bob Lomerson, Westinghouse, Newberry Park, Calif.) I would be interested in knowing if you came to any conclusions during this study as to the optimum pin arrangement. By this I mean did you find that a TO-5 configuration was better than a radial or let us say quadrilateral or bilateral symmetry coming out of the side, four sides, two sides, the bottom or what? For logic circuits, what do you think would be the best arrangement?

A. In the construction of these modules I used the logic devices that were available at the time. The best arrangement seems to be a flat square or rectangular package with the leads projecting out of two sides. This allows the construction of a very small and compact system.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) In your conclusion there appeared to be an inference that these packaging densities, which run to three and four millions, when reduced by actual system design integration, would be about the same order of magnitude that we are currently achieving with less exotic devices. Did I interpret this correctly or is this extrapolating your inference too much?

A. I said that this figure would be degraded to a certain point but I didn't say how far. I did state that the densities obtained were only for the modules. When you design a system, you have to take into account the structure, interconnections, mounting hardware, and possibly heat transfer media. When the overall system volume is computed, the packaging density figure will be quite radically reduced. A system of standard or less exotic components, will not approach the weight and size attainable by the use of these devices even though the packaging density for the integration system is greatly reduced over the modular figure.

Q. (Wayne Plunkett, Army Missile Command, Redstone Arsenal, Ala.) I noticed your electrical connection tabs are very short. What kind of connector do you plan to plug this into?

A. These modules were not designed to plug into a connector, although they could be. They were designed to be assembled to a notched printed circuit parent board and be soldered in place. The T.I. computer makes use of a connector, which the assembled modules plug into.

Q. Do you have the manufacturer's name of the connector?

A. The connectors are manufactured by Airborn Connectors Inc. of Dallas, Texas.

Q. (Ordean Joachim, Univac, St. Paul, Minn.) On your Fairchild assembly what did you use as an insulator between the tops of the devices and the interconnection patterns on the opposing circuit board?

A. There is a clearance of approximately $\frac{1}{32}$ in. between the devices and the interconnection paths. This spacing is held by the riser or interconnecting wires between the two boards. When the device is encapsulated, epoxy occupies this volume providing a $\frac{1}{32}$-in.-thick insulating medium between the device and the conductors.

A Packaging Method for Thin-Film Microelectronic Systems

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This paper deals with a packaging technique for the assembly of thin-film circuitry, and is intended to show how engineering ideas can become packaged microelectronic hardware with maximum efficiency. Included in the presentation is a review of thin-film processes, discussions of the basic packaging system and logic circuitry, as well as consideration of pertinent environmental factors.

INTRODUCTION

THIS PAPER discusses a packaging concept for the assembly of thin-film circuitry for experimental and engineering prototype equipment. The purpose is to show how engineering ideas can be turned into packaged microelectronic hardware with maximum efficiency. The packaging system (and the thin-film technique) is designed for a quick-reaction capability, with the volumetric efficiency, appearance, and quality needed to demonstrate thin films as a microminiature equipment fabrication technique.

A set of applicable package goals aimed at this capability is as follows:

1. To have quick reaction the packaging system should employ stock "off the shelf" standard parts.
2. To meet experimental requirements the package should be flexible enough to meet the requirements of a number of different applications.
3. For purposes of maintainability, the package should be completely pluggable and repairable down to the lowest component level. All wiring should be flexible and exposed so that system changes or failure diagnosis can be made.
4. The package should have the routine prerequisites of any good package; that is, it should protect the contents from the environment, have an attractive appearance, good heat transfer and, of particular importance, a minimum contribution to the system's weight and volume.

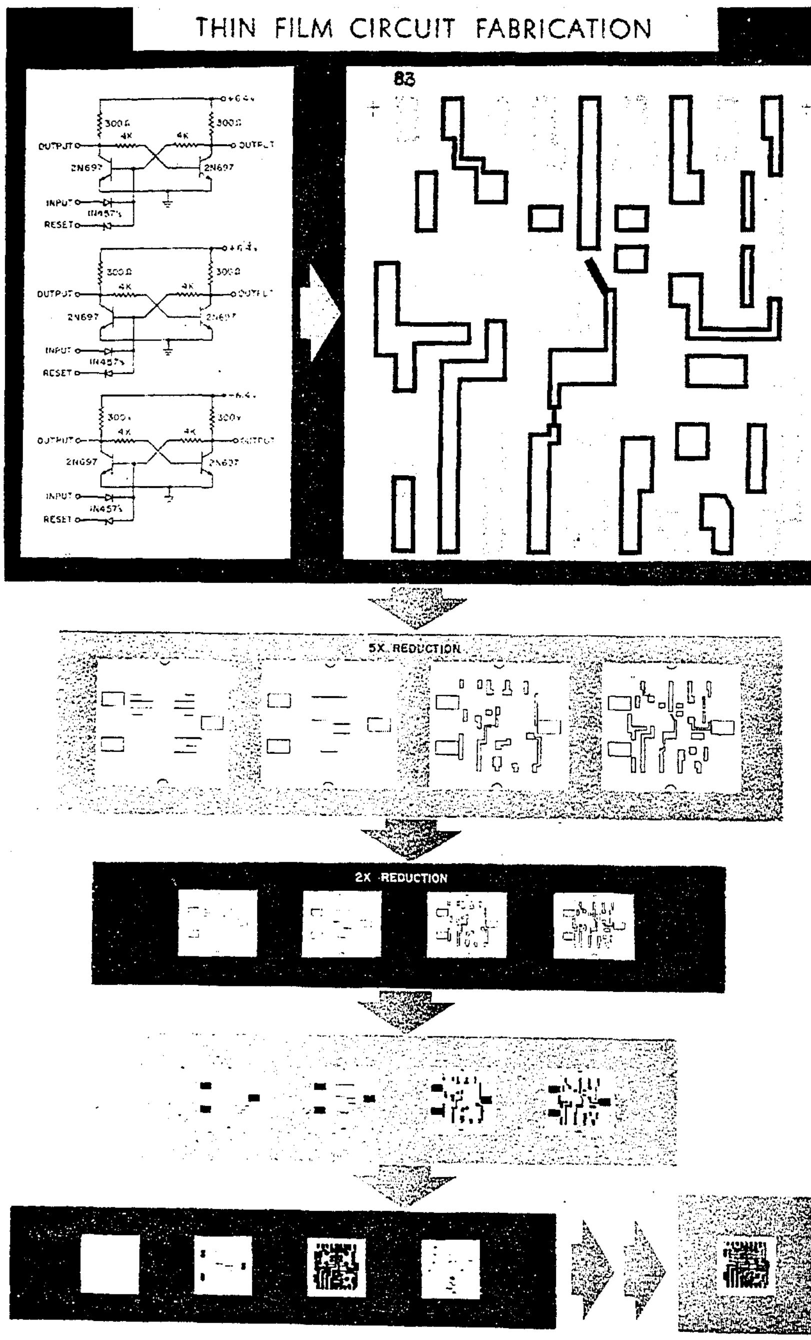


Fig. 1. Thin-film circuit fabrication cycle.

REVIEW OF THIN-FILM PROCESSES

It might be well to review the processes and techniques of thin films since thin films are a rather abrupt departure from the conventional components normally encountered in packaging. Also discussed are those factors in thin-film processes and techniques which are controlled by packaging considerations.

Basically, the technique described here is for packaging 1 × 1 × 0.020 in. substrates. The passive components—resistors, conductors, and capacitors—are vapor-deposited. The active components—micro diodes and transistors—are thermocompression bonded on these substrates to complete the circuit.

The basic starting point is a system block diagram and circuit schematics. Decisions must be made as to how much and what circuitry goes on a substrate, how much of the interconnection complex can be placed on the substrate, and how the final package is to be interconnected. The process from schematic circuit to a finished circuit substrate is shown in Fig. 1. This illustration shows the development from schematic to the substrate for three flip-flops on one substrate. In this case four masks are made for depositing resistors and conductors. (The four finished masks are shown next to the bottom row of Fig. 1.) The masks are made of beryllium copper by means of the photoetch process. The materials to be deposited on the substrate are vaporized from a heated filament in a vacuum bell jar. The masks cover the substrate and control the patterns to be deposited on the substrate. The resistors are deposited nichrome. Electrical crossovers and capacitor dielectrics use silicon monoxide as an insulator. Conductors are gold or aluminum over chrome. Chromium is used to give film adhesion and scratch

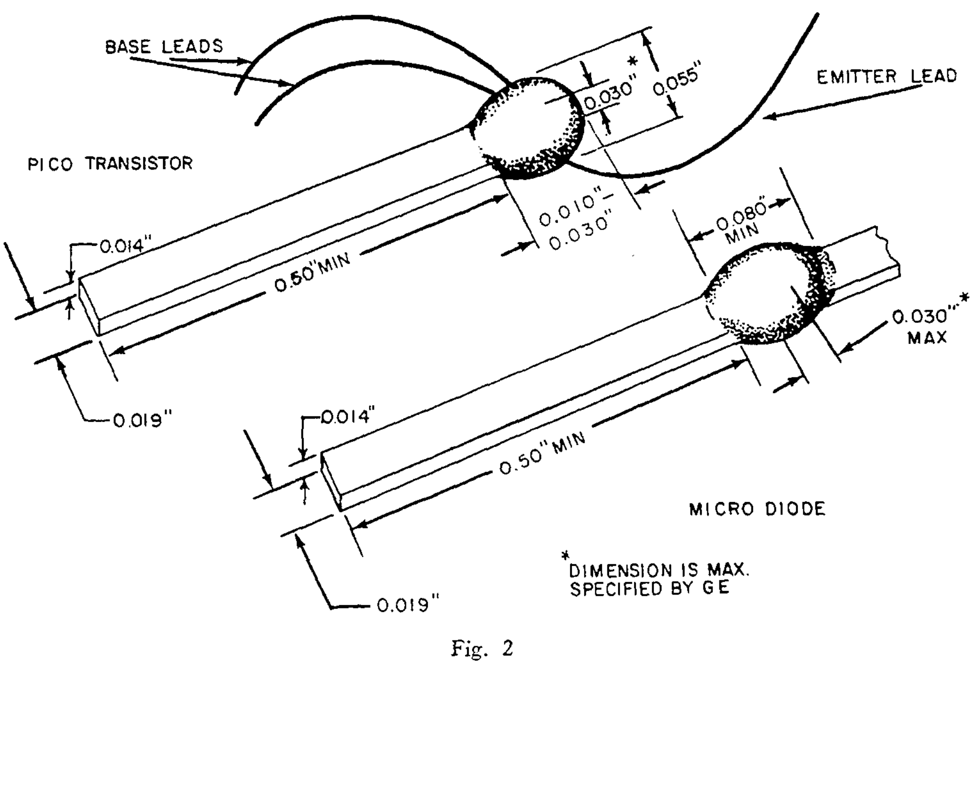


Fig. 2

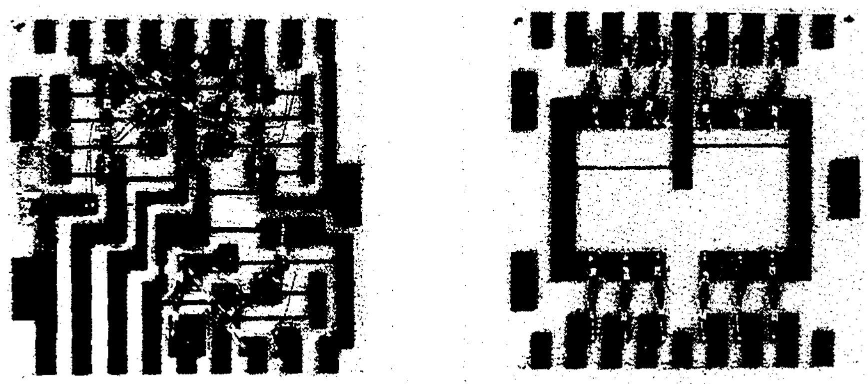


Fig. 3. Three-flip-flop substrate.

resistance for the friction contacts. There are nine contacts (0.050 in. wide on 0.1-in. centers) on two edges of the substrate or a total of 18 contact pads. The semiconductors to complete the circuit are shown in Fig. 2. The circuit on the substrate is completed by thermocompression-bonding the necessary wires and semiconductors in place. Thermocompression-bonding is a form of welding using a heated wedge and pressure to secure a molecular bond between the 1.5- to 3-mil diameter gold wire leads and thin film on the substrate. A detailed view of the completed three-flip-flop circuit substrate of 16 resistors, 6 transistors, and 6 diodes on a 1 × 1 in. substrate is shown in Fig. 3.

BASIC PACKAGING SYSTEM

The basic packaging system to hold these substrates consists of four "off the shelf" standardized parts: (1) the half module (two of which are required to make

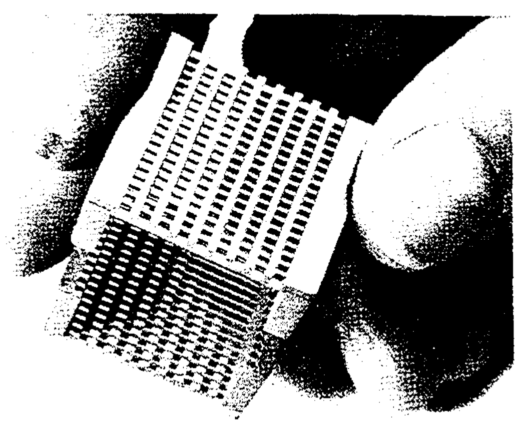


Fig. 4. Half-module.

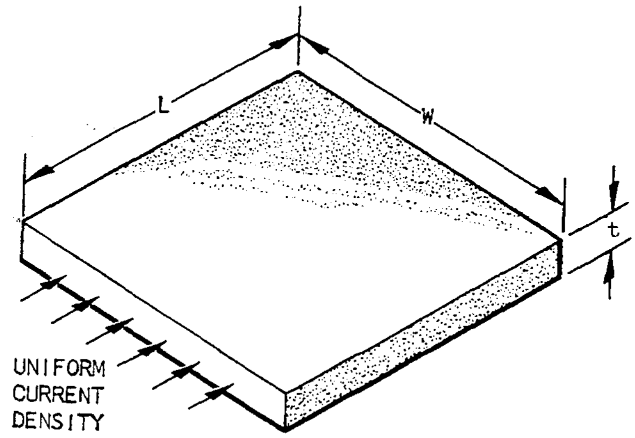
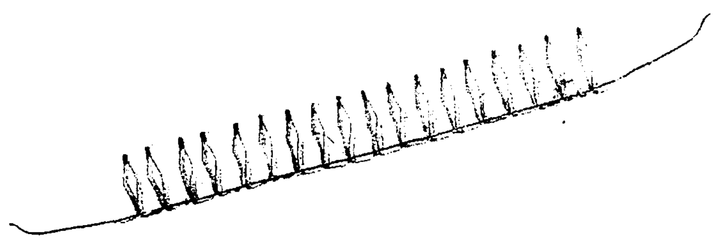


Fig. 5

SIDE VIEW



TOP VIEW

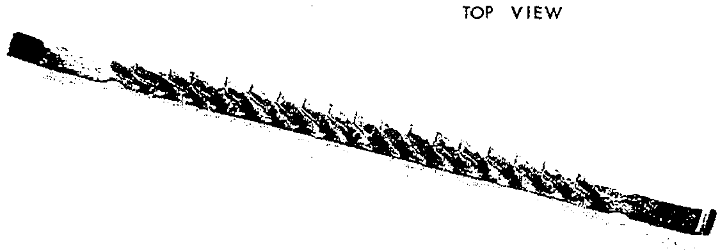


Fig. 5a

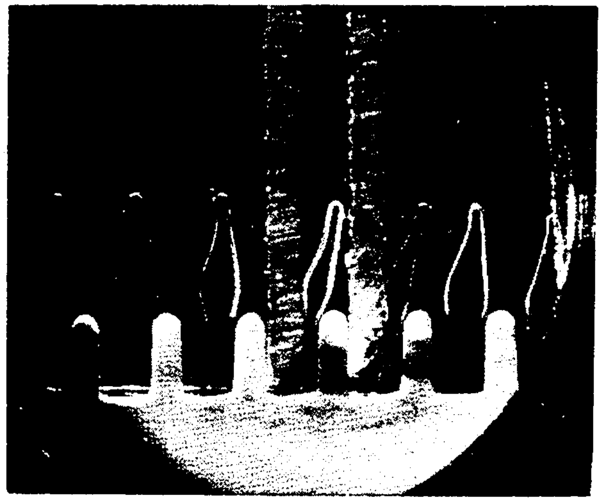


Fig. 5b. Contact strips in place.

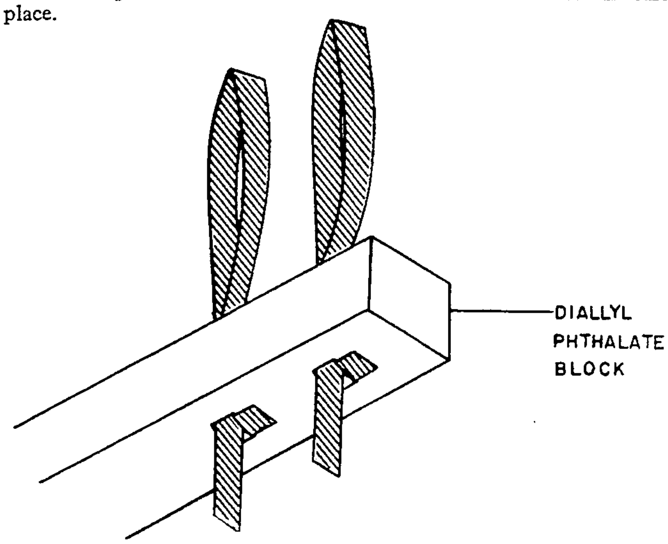


Fig. 5c. Independent contact strip.

a whole module), (2) contact buss bar strips, (3) the module cap, and (4) the module socket.

1. *The half module* (Fig. 4) holds 18 substrates on 0.050-in. centers by means of 18 internal grooves in a diallyl phthalate plastic part. On the external face nine grooves lengthwise on the module break through to allow access to the contact pads on the substrate.

2. *The contact buss bar strip* (Fig. 5a) consists of a gold-plated beryllium copper wave strip which makes electrical contact with the contact pads on the substrate and a backing strip which carries the signal to the external grooves. Up

to 18 contact strips can be used for each module assembly. A detail of how the contact loop of the strip is compressed and locked into place by the substrate to make a reliable contact to the substrate pad is shown in Fig. 5b. An independent electrical contact mounted in a diallyl phthalate strip to make a point-to-point wiring scheme possible is shown in Fig. 5c. An open module half with contacts in place is shown in Fig. 6. The basic package might well be described as a microminiature socket. For 0.9 in.^{3} of substrate there are 324 contacts.

3. *The module*, complete with end cap, is shown in Fig. 7. This photograph shows the dual function of the end cap to protect the end substrate and to support the buss bar, thus permitting it to mount in a female connector.

4. *The module socket* or female connector is also shown in Fig. 7. These four elements comprise the complete packaging system. Eight uninterrupted buss bars are shown in Fig. 7. This type of interconnection would be suitable for signals or voltages common to all substrates.

The adaptability and versatility of the module enable it to meet the stated objectives. The plastic frame can be modified so that any size of 1 in. by X in. substrate can be used and the number of substrates can be varied from 1 to X by cutting down a single-frame module or adding on additional modules. Single or

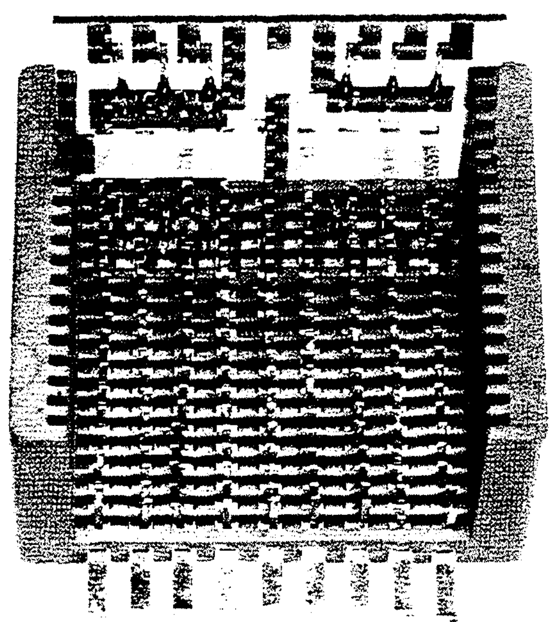


Fig. 6. Photograph of package.

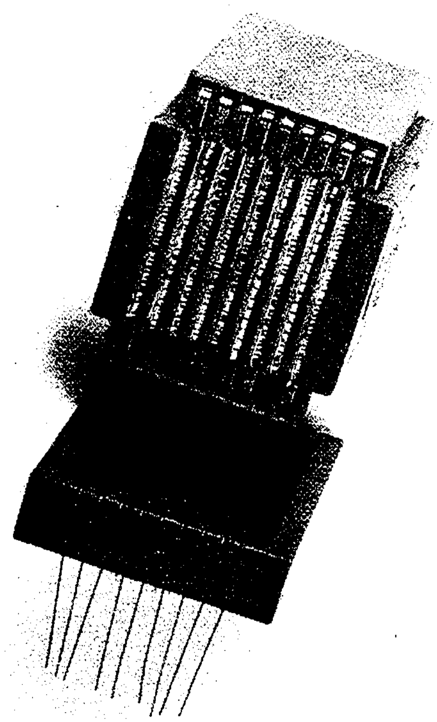


Fig. 7. Complete packaging system.

multiple connections can be made to the substrate by single contacts, partial buss bars, and completed buss bars.

Two examples of an interconnected package will be reviewed: a fairly complicated diode logic computer circuit and a less complicated redundant logic circuit.

DIODE LOGIC COMPUTER CIRCUIT

Rather misleading results may be obtained if packaging studies are confined to circuits such as multistage amplifiers, adders, shift registers, counters, etc. These circuits are relatively simple to lay out on substrates and to interconnect using the buss bars. These are essentially series-type circuits, where the signal flow progresses down a row of circuits. In the digital computer area the predominant system consists of groups of circuits called logic circuits, which perform actions and counteractions based on data from several different paths. Figure 8 is an engineer's preliminary sketch showing such a system. This sketch serves to illustrate a system of wired diode logic of a type that is often encountered. Such sketches are generally not used; instead, deceptively simple block diagrams with wiring tables serve to indicate interconnections. One way of characterizing the interconnection complexity is to cite the fan-in and fan-out ratios. A simple serial

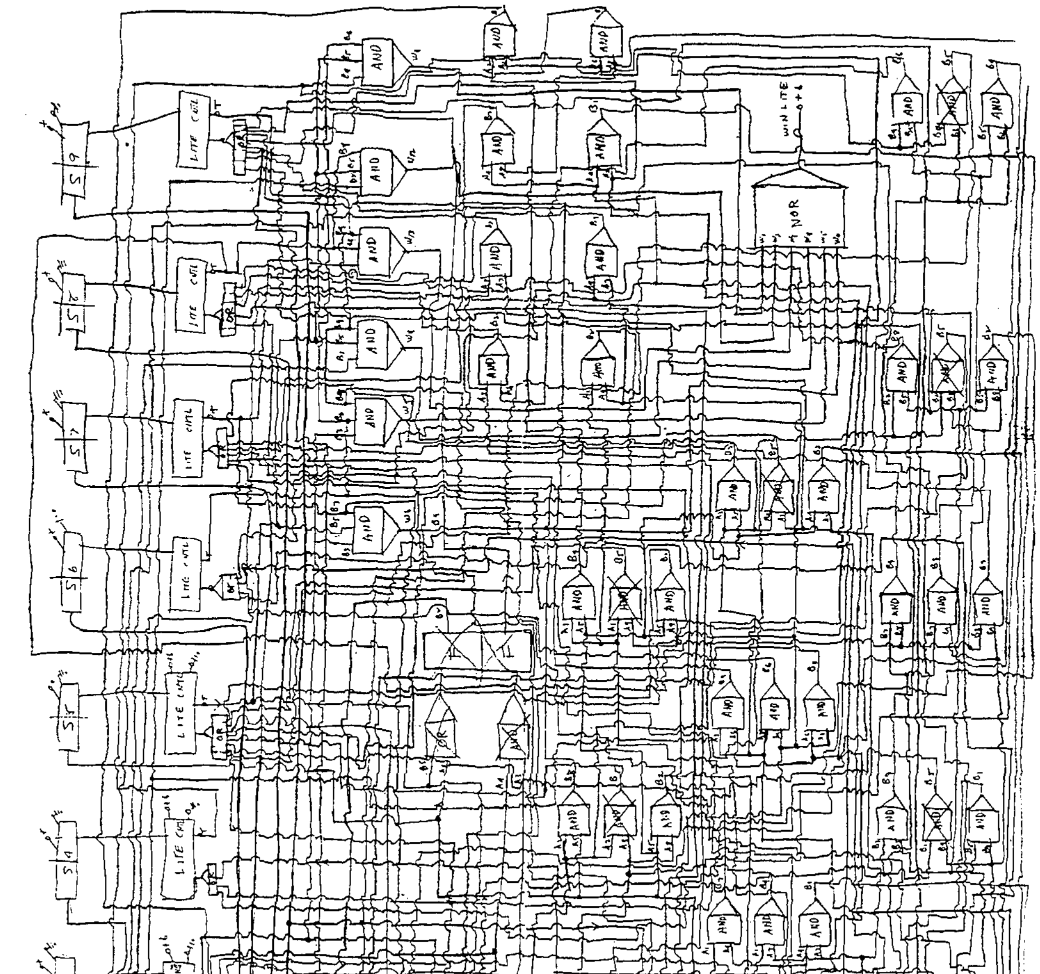


Fig. 8. Preliminary sketch of a diode logic computer.

circuit has an input and an output. Here each of these circuits, on an average, fans out to 15 other circuits, where the process is repeated. One input is soon contributing to the controlling signals on some 200 wires. This particular system then begins to fan-in, in the same manner as it fanned-out.

Attempts to analyze this system to minimize the interconnection problem by logical groupings of deposited circuits were unsuccessful. Basically, circuits were laid out to avoid crossovers, to group similar circuits on the same substrate, and to minimize the number of types of circuit substrates required. The example of three identical flip-flops shown in Fig. 3 is from this system.

The maintenance of the 0.1-in. center between contact pads is an electronic industry standard and limits the substrate to nine contact pads on two edges. Following this standard the number of components that can be mounted on a substrate is limited by the ability to terminate circuits.

Statistically, the digital diode logic computer consisted of 375 diodes, 65 transistors, 266 resistors, and 16 capacitors on 46 substrates of 10 different types. Some connections were made on substrates. There were 602 points to be interconnected externally. In theory, if point-to-point wiring were used, 301 bits of wire would have interconnected the package. Over 300 ft of wire were used to interconnect the breadboard shown in Fig. 9. However, the entire computer will package into the module being held by the engineer. The size of this module, shown in more detail in the inset, is $3 \times 1\frac{3}{16} \times 1\frac{1}{4}$ in. or 4.85 in.^{3}.

Two systems of interconnection were investigated and carried through the "proof of feasibility" stage. One system of interconnection is the *Amphenol*

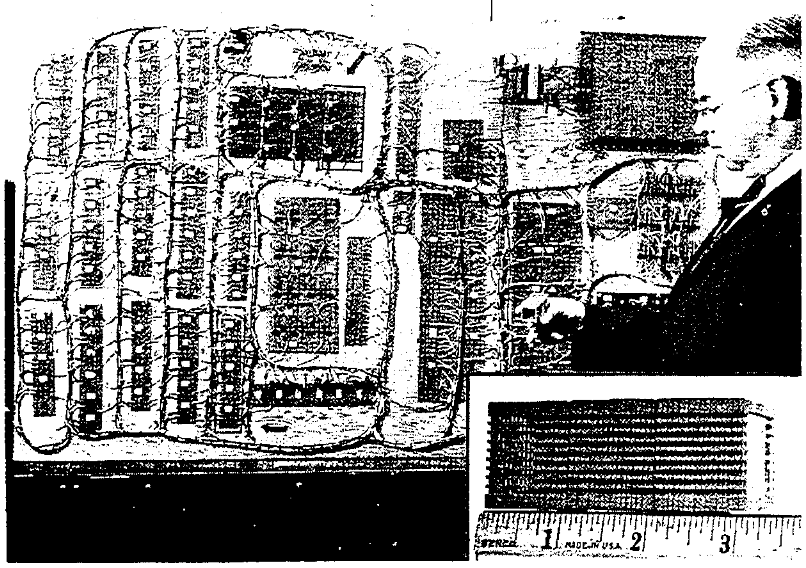


Fig. 9. Breadboard system and actual module.

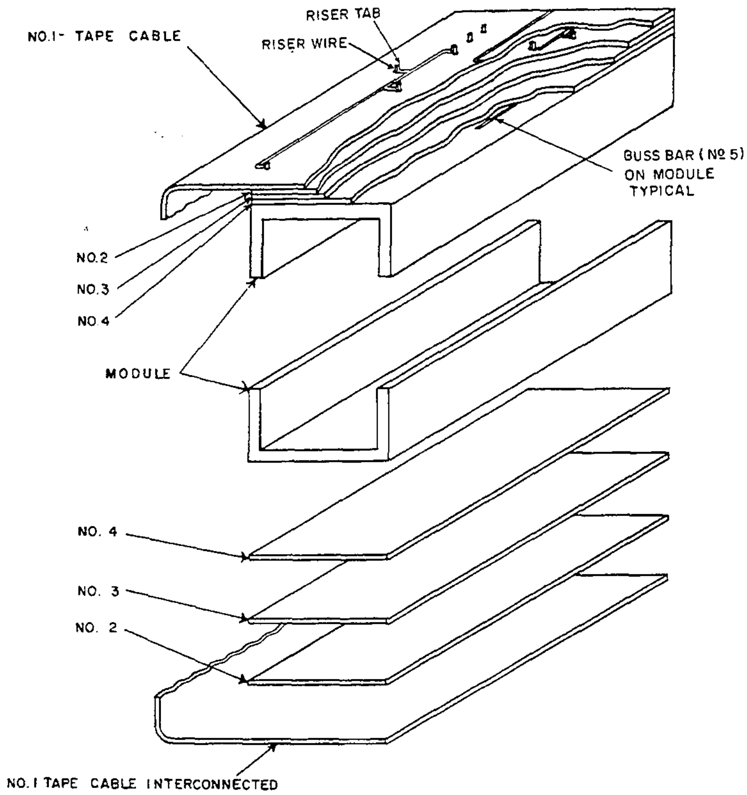
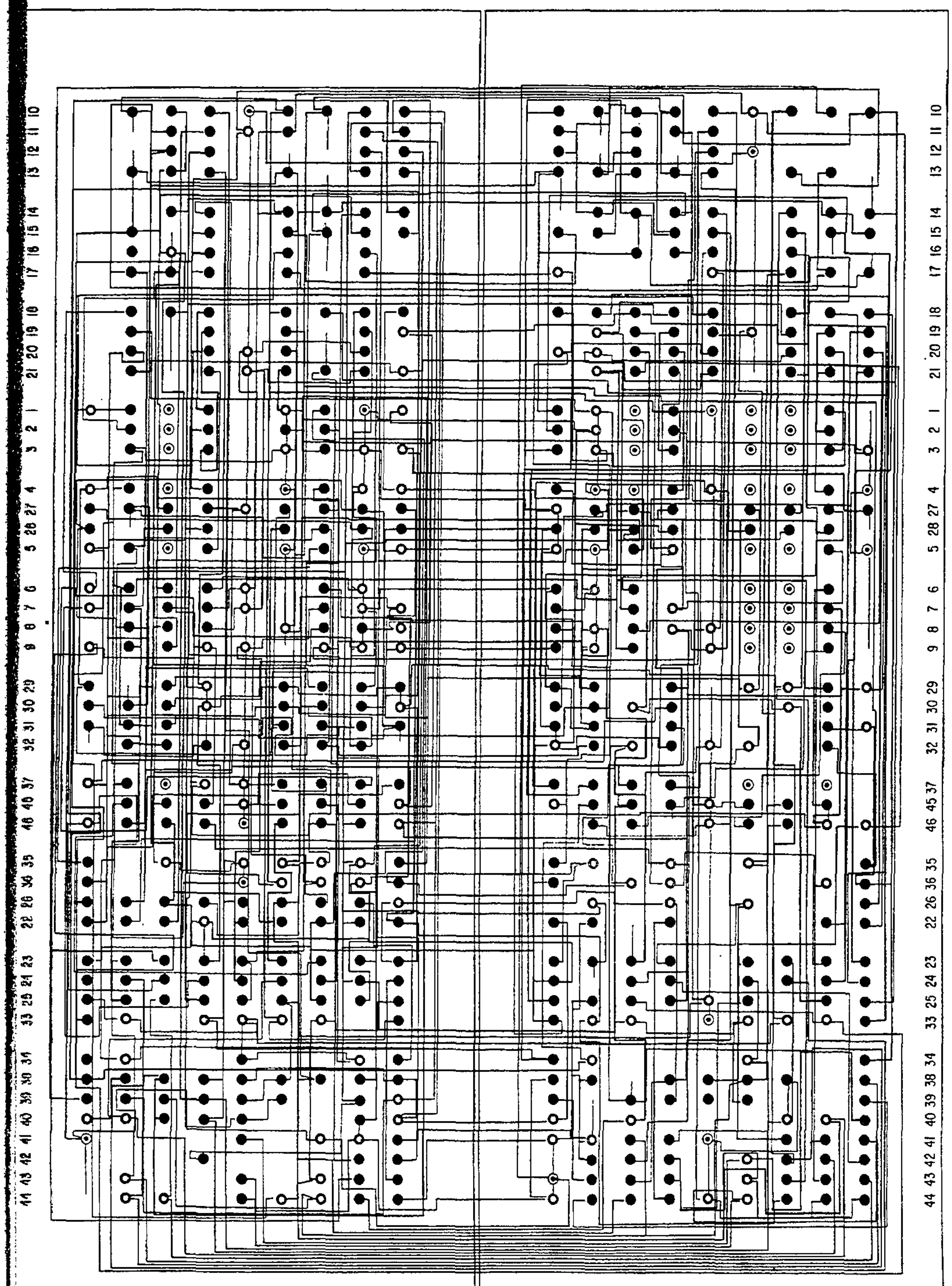


Fig. 10

Intercon system. The system could be interconnected with a multilayer board consisting of three rigid layers and one flexible layer and a few contact strips. The arrangement of the four layers is shown in Fig. 10. In the Amphenol system a bent-up tab provides the area for a welded or soldered joint. The bent-up tab also provides the means of interconnecting different layers in the sandwich. Figure 11 shows the interconnection function accomplished by the Intercon system.* Lines shown in green are contact strips in the grooves. Red lines are on the top flexible layer. This layer not only interconnects but carries 75 wires around the module. Blue, yellow, and black are the intermediate layers. The large black dots indicate connections from the independent contacts to the circuit boards. The small dots in circles indicate connections to the substrate that go to the board and to the 32 points external to the module. The concentric circles are tabs for interconnections between layers. In practice the ability to use four layers and to transfer from layer to layer made layout comparatively simple. Conductor runs are 0.008 in. wide and 0.004 in. thick with a 0.006-in. spacing between conductors. Tabs extend 0.030 in.

* Figure 11 could not be reproduced in color and appears in black and white for whatever value it may have. The authors' words, however, remain as they were written.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17 16 15 14
21 20 19 18
3 2 1
5 28 27 4
9 8 7 6
32 31 30 29
46 45 37
22 26 36 35
33 25 24 23
44 43 42 41 40 39 38 34

Fig. 11

TABLE I

Diode Logic Computer Circuit Package

Number of Components	Description
375	Micro Diodes*
65	Pico Transistors*
266	Resistors (thin-film)
16	Capacitors (thin-film)
Total 722	

Volume of circuits (1 × 1 × 0.050 in., 46 plates)	2.3 in.^{3}
Parts per cubic inch (gross)	313 parts/in.^{3}
Volume of package (1.125 × 1.2 × 3 in.)	4 in.^{3}
Volume of interconnection (0.065 × 3 × 2 in.)	0.4 in.^{3}
Interconnected parts per cubic inch	164 parts/in.^{3}

* Pacific semiconductors.

above the board to allow a means of connection by soldering or welding. The multilayer board is 0.065 in. thick and takes up a volume of less than 0.4 in.^{3}. The cost of the engineering and artwork for a circuit of this complexity was approximately $3500. The prototype board cost $450, but in quantity the cost would be less (probably $100).

Another system of interconnection was also studied. This system employed a single-layer wrap-around printed-wiring board. Eight additional substrates were designed to take care of many of the interconnections what would have wrapped around the module. Approximately 5% of the connections were made by single-layer point-to-point wiring. The printed-wiring board employs conductors of 0.005-in. minimum width with 0.005-in. spaces. With solder lands around the holes, this would allow for one conductor run on the 0.050-in. center between substrates and three runs on the 0.100-in. centers between lands.

Both these systems represent an interconnection capability compatible with the microminiaturization of the circuits themselves. Table I summarizes the statistics relative to this package.

REDUNDANT LOGIC COMPUTER SYSTEM

The second example of an interconnected package is one used as the microportion of a small *redundant logic* computer system. It will serve to demonstrate the value of an integrated microelectronics program.

The block diagram of the redundant logic system is indicated in Fig. 12. In this system there are some definite and repeating portions. The half-adder blocks consist of 12-transistor–30-resistor circuits and will go on a substrate. The flip-flop blocks consist of 4-transistor–9-resistor circuits. Three flip-flops can be deposited on a substrate. In addition, it is possible to deposit the signal and supply

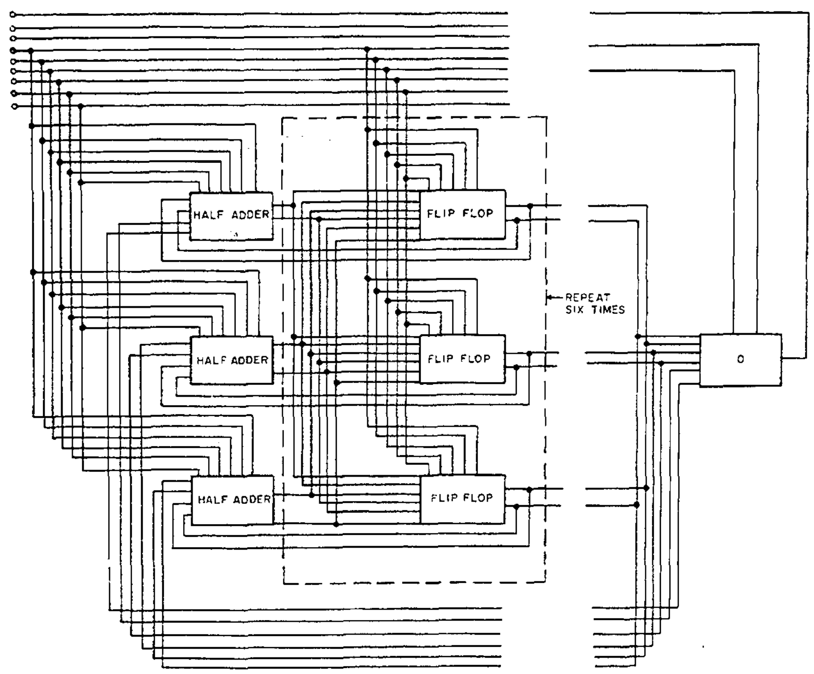

Fig. 12. Redundant logic system.

voltage networks thus drastically reducing the interconnection problems. The circuitry within the dotted line goes on one substrate. The General Electric 18-pin plug has connections to spare for the 8-input–1-output lead required by the module. Five continuous contact strips take care of the supply and clock voltages. Twelve grooves with short lengths of contacts perform the function of interconnecting the signal leads. Point-to-point wiring is used for the balance of the interconnections three leads from the output substrate, and the six feedback leads to the half-adder substrates. Figure 13a is a photograph of the half-adder substrate showing the wiring network which changes the substrate termination pattern to match the interconnections. A similar technique is employed on the flip-flop substrate shown in Fig. 13b. The completed module with an outer plastic cover to protect the package is shown in Fig. 14.

How many parts per cubic foot can be obtained with thin films disregarding the packaging problem? Figures 13a and 13b show that fully half the substrate area is taken up by elements properly credited to the interconnection problem—the terminating pads and the termination patterns. The actual circuits occupy an area about 0.5 × 0.8 in. A 0.020-in.-thick glass substrate is being used, primarily for packaging and maintenance reasons. These circuits can be deposited on 0.010-in. glass or ceramic substrates. There is now a 0.030-in. clearance between substrates for the semiconductors. With proper semiconductor layout two substrates can be placed face to face with the semiconductors nesting for a net space

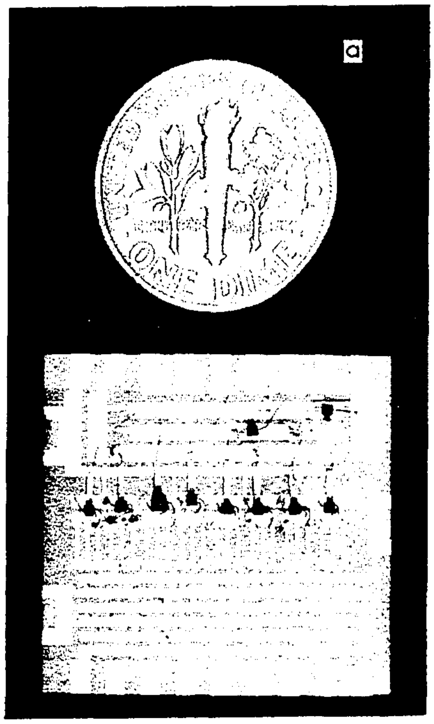

Fig. 13a. Half-adder substrate.

b

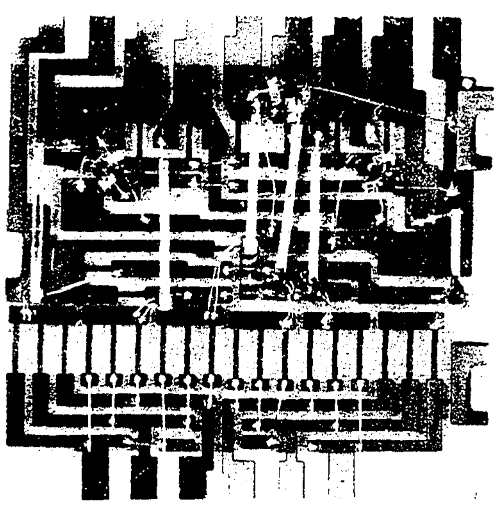

Fig. 13b. Triple flip-flop.

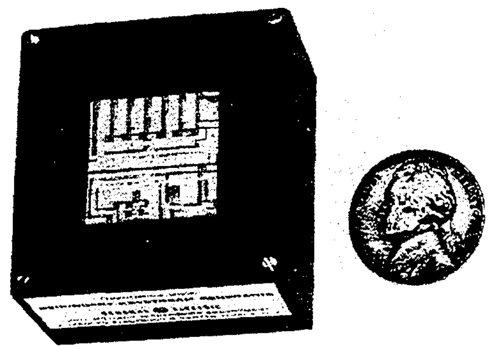

Fig. 14. Redundant logic package.

usage per substrate of 0.015 in. This circuit could be 0.5 × 0.8 × 0.025 in. thick or 0.01 in.^{3}. The present layout of the half-adder would pack 46 parts in this volume or 4600 parts/in.^{3} or 8,000,000 parts/ft^3. In practice, however, the logic package as shown is down to 512 parts (112 transistors and 400 resistors) per cubic inch (890,000 per cubic foot); with plug and socket included it would be 335 parts per cubic inch (582,000 per cubic foot).

ENVIRONMENTAL FACTORS

There are a number of problem areas that were anticipated but not encountered. One problem was electrical interference. It was thought that mounting these essentially flat unshielded circuits 0.050 in. from each other might lead to a mutual interference problem. The redundant logic circuits operated up to 5 Mc without any sign of interference or other instability caused by the close proximity of the circuits or the lack of consideration given lead dress or shielding.

Another problem in microelectronics is heat transfer. The diode logic package cited had a power dissipation of 7.5 w. This is a little over 2 w/in.^{3}. Power dissipation by natural convection tests were run with a uniform distribution of 2 w/in.^{3} generated by substrates within the module. These conditions resulted in a 30°C hot-spot temperature rise over ambient at the midpoint of the middle substrate. At 5 w/in.^{3} a 70°C rise was observed. A solid block of this size and with this power distribution would have a core temperature two to three times these observed temperatures. This is one advantage of the unpotted, independent parallel plate approach to packaging. In this package the heat generated on a plate tends to flow to the outside rather than across the air gap to the next plate. Incidental convection currents and air leakage in the 0.030-in. gap between substrates tend to equalize temperatures. With slotted walls, and air flowing directly by the 30 to 36 in.^{2} of heat transfer area (the 18 substrates), a power dissipation of 5 w/in.^{3} results in a reasonable 40°C temperature rise under free-convection conditions.

Forced convection would result in further cooling. The redundant logic package has a total dissipation of $\frac{1}{4}$ w. The credit goes to the circuit designers and the transistor suppliers. With better transistors, glazed aluminum oxide substrates, and knowledgeable circuit design, power dissipation should not be a packaging limitation for years to come. The basic packaging limitation now seems to be in the interconnection area. The limitation is made up of such common things as the allowable current-carrying capacity of wires or the minimum spacings between conductors when electrical leakage or arcover become a problem.

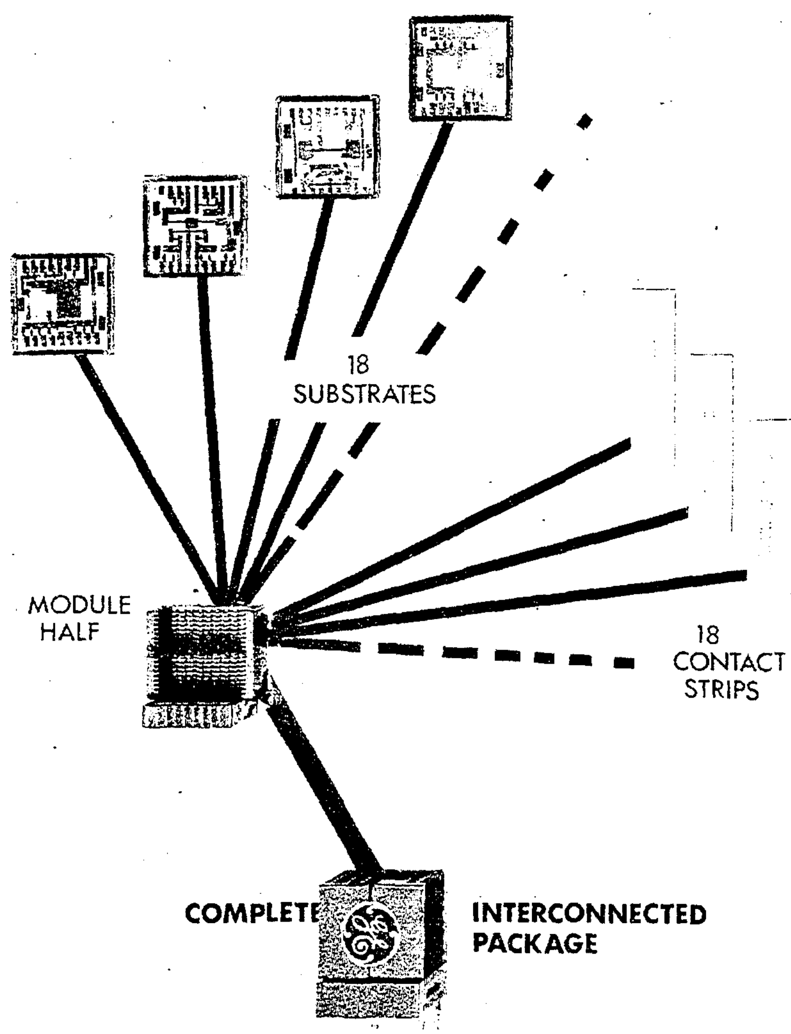

Fig. 15. Microminiaturized electronic packaging.

SUMMARY

A packaging system (Fig. 15) for thin-film microelectronic circuits has been developed that is:

1. *Flexible.* The package will accommodate a variety of substrate sizes as long as the basic nine contacts along a 1-in. side are used; the package can be interconnected by buss bars or point-to-point soldering or welding, or it can take advantage of the most sophisticated printed circuit interconnection techniques. The circuits are plugged into the interconnections array so that a set of standard circuits can be used in an endless variety of different logic arrangements. Depending on the type of interconnection employed, changes can be made on the interconnections after the module is completed and tested.
2. *Maintainable.* The package is adaptable to a multilevel maintenance philosophy. The module is a discrete unit and at the field level a replacement module is as simple to replace as a tube or transistor. At the depot level a stock of spare circuits (complete substrates) would serve to keep the modules operable. If desired, even more detailed repair and maintenance can be conducted at the substrate or semiconductor level.
3. *Potentially Reliable.* The module is resistant to shock and vibration and does an excellent job of cooling the substrates and preventing hot spots. Simple shrinkable plastic cases are adequate to seal against moisture and atmosphere effects. In an experimental application the package is attractive in that reliability data can be acquired down to the component level.
4. *Efficient.* The employment of a flexible but standard packaging technique substantially reduces the costs and lead times for turning out prototype equipment. The package makes a minimum contribution to the system's weight and volume.

A successful method for packaging thin-film circuits has been developed. It is hoped that these techniques will be applicable to the continuing development of microminiaturized electronic equipment.

DISCUSSION

Q. (Stuart E. Hotchkiss, RCA, Princeton, N.J.) I would like to inquire a little bit on details concerning your masks. First of all, do you make your own masks?

A. Yes. We make our own masks.

Q. How thick are these masks and how thick a layer do you deposit by evaporation?

A. The thickness of our masks depends on the tolerances that are required. We use 1- to 5-mil beryllium copper. Better tolerances (but fragile masks) are obtained with the thinner material. These are essentially thin-film circuits. We estimate that the resistors are on the order of 1000 Å or less. The conductors are about 1μ. We measure the resistance of the films as they are deposited and not the thickness.

Q. The reason I inquired about the thickness was that you mentioned that you had layed down a gold conductor approximately 1½ mils wide and you presumably have etched a 1-mil beryllium copper mask.

A. The conductors you are referring to are probably the fine vertical conductors shown in Figs. 13a and 13b. These conductors are 1½-mil gold wires thermocompression-bonded to the thin-film circuit.

Q. These are actually wires?

A. Yes.

Q. (Kenneth Tillmanns, General Dynamics, Pomona, Calif.) What do you use for the minimum width of resistors and conductors and the spacing between them?

A. Resistors are either 5 or 10 mils wide, with better tolerances available on the 10-mil resistor. Conductors are a minimum of 20 mils with an 8-mil spacing. We essentially fill the available space with conductors and make them as wide as possible.

Q. (Max Alper, Giannini Controls, Duarte, Calif.) What sort of protective coatings, if any, do you use over the deposited circuitry?

A. It was not too apparent from the slides, but if you look carefully at Figs. 13a and 13b you will note that there is an almost transparent coating over the entire circuit but not covering the contact pads. The material is silicon monoxide.

Q. Is that applied after the semiconductors are put on?

A. No. The silicon monoxide is applied as the last step in the vapor-deposition sequence.

Q. And then the semiconductors are thermocompression-bonded?

A. Yes. A small chip of silicon-monoxide is removed exposing the gold chrome conductor to which the lead wires are thermocompression-bonded.

Q. About how thick is that coating?

A. The thickness is not specified too closely. It is about 2 μ.

Q. (Bob Bender, Hughes Aircraft, Newport Beach, Calif.) I have two questions. General Electric has announced a small leaded microdiode. I wonder if you had used any of these. The second question. In a sheet called *Breakthrough* I recently read that G.E. had announced the abandonment of the thin-film program for nontechnical reasons. Would you care to comment?

A. In answer to your first question about G.E. diodes—we have not used G.E. components. We have been working with and using Pacific-Semiconductor Components for the last three years. As to the second question—G.E. is a decentralized company with each department and operating component making its decisions essentially as an independent business. The department quoted in *Breakthrough* and in the trade journals had the responsibility for sales of thin-film circuits and thin films as components in external (to G.E.) markets. Efforts leading to thin films as a product line have been abandoned. One of the reasons is that the large users of thin-film circuits have their own internal thin-film programs capable of supplying their own particular needs. Within G.E. the departments building electronic equipment are very active in the area of thin films, but the end product is electronic equipment using thin-film circuit elements.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) I would like to know what techniques you suggest for the interconnection of these multiwafer modules? I notice you are using the Amphenol connector.

A. We are using some of the parts of an Amphenol connector but they have been modified. This connector terminates the module. The connector can be soldered into an interconnecting wiring board to go to other module connectors or the rest of the system. Since a module can contain 1000 or 2000 parts, most of the systems of the size we build contain only one thin-film module, interconnected to more or less standard circuitry.

Q. I would like to compare your experience with mine on the use of that particular connector. I know our experience has been very poor even under laboratory conditions, let alone environmental tests. I wonder if you have had the same problems?

A. We haven't had much experience with this connector. The contacts on our connectors are somewhat different than the normal connector you buy from Amphenol. Our limited experience has been satisfactory. The connector was used to carry signals in and out in the vibration tests we performed on the module.

Q. (W. J. Giguere, Bell Labs, Murray Hill, N.J.) It seems to me that in trying to build redundancy in and also trying to put your redundancy unit all on one substrate is putting a great deal of faith in the reliability of the contacts and connectors. Would you like to comment on that?

A. Yes, I will agree with that. Redundancy has not been carried to its logical conclusion. We have some redundant contacts but there are still four or five contacts which, if open-circuited would take out the system. More thought in layout might have avoided this problem. A more desirable solution would have been to distribute the three redundant circuits onto three different substrates since there are dependent modes of failure on a single substrate.

Q. (Don Schnorr, RCA, Camden, N.J.) Would you elaborate somewhat on your method of distributing power to the module? I notice that you have six buss bars, and it looks as if they are connected to the tabs with fine wire. Is that true?

A. The contact buss bar strip (Fig. 5a) makes power available to each substrate. The wave strip makes a friction contact to the vapor-deposited land or tab on the substrate. In some cases, such as in Fig. 13a, fine wire is used to connect the tab to the other conductors on the substrate.

Q. Did you mention the diameter of these wires?

A. These are 1.5-mil-diameter gold wires thermocompression-bonded in place. You may well ask why we use this technique since we could have vapor-deposited these conductors. First, although we have only three different half-adders, some nine additional masks and deposition steps would have been required to vapor-deposit the networks shown. Since our total production requirement was only one substrate of a given requirement, it was more economical to deposit the common elements and use the wire jumpers to modify its terminations.

Q. (John Rykaczewski, Martin, Orlando, Fla.) One of your packaging goals was maintainability down to the lowest component level. In your paper you say that the resistors are deposited nichrome. How do you maintain them?

A. You do it by pulling the substrate out and slipping a new one in under the semiconductors. We can carry diagnosis down to the level of the individual nichrome resistors, but if one or more of them is defective the substrate must be thrown away. We would salvage the semiconductors but this is a matter of economics at a given point in time.

Q. (R. McMillan, Hughes Aircraft, Fullerton, Calif.) On the glass substrates, what was the material that you were using for a conductor? What is its thickness—since you are using it as a friction or wiping contact?

A. We have very hard, abrasion-resistant contact pads and conductors. The abrasion resistance is obtained by depositing chromium on a hot substrate. Over this is a top layer of a conductive material such as gold or aluminum. We estimate that the layer is about 1-μ thick. We monitor resistance during deposition and deposit the chrome to 50 ohms per square and the top conductor to about 1 ohm per square. We sometimes heat-treat the sandwich further to obtain a more durable film. When we are finished we have to gouge the glass in order to open a conductor run.

Microcircuitry: An Approach to the Fabrication of Microelectronic Circuitry

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This paper presents a description of the development and pilot production of microelectronic circuitry at Sylvania Electronic Systems. Special attention is given to material and process requirements and the special production equipment that had to be developed.

IN YEARS PAST, electronic hardware was elementary in nature. The chief design requirement for an electronic circuit was to satisfy the performance requirements of the system, and since early systems were relatively uncomplicated, the problem of packaging of the required components within the available space so as to meet reliability and cost requirements was straightforward and of secondary importance. With the advent of the transistor came an increasing demand for system complexity, to the point where in the military systems of today, while circuit designs are still generally within the state of the art, the problems of forming and creating this highly complex circuitry and interconnecting it (packaging) have almost become the predominant factor determining system reliability and cost. This demand for the creation of complex electronic circuits and their interconnections into systems with greatly reduced space and weight and the need for a corresponding increase in reliability have given rise to the general field of microelectronics.

Going beyond even some of the advanced methods of assembling individual standard electronic parts into functioning blocks of circuitry, we in the microelectronics field are occupied with the more basic task of developing methods of forming electronic circuits on an end-use substrate from raw materials. For a limited number of circuits some existing technologies appear to be able to do this, but we cannot neglect the demands of other systems and circuits. We must, if necessary, compromise with current capabilities by combining attached electronic components with microelectronic circuits formed by vacuum vapor deposition or silicon-base circuit formation.

The objective of this paper is to show the Sylvania Electronic Systems microelectronic circuit formation and packaging approach. The keynote of this approach has been the satisfaction of circuit and system demands, without performance compromise. This, combined with an ability to create and apply advanced circuit formation technology, permits continuing growth of our circuit capability and our packaging technology. Throughout the program, a primary concern has been to provide the designer with maximum flexibility in parts selection. Very small size and light weight with very high reliability must be implicit in our techniques of material selection, circuit formation, and test and protection.

The ultimate objective of the Sylvania microelectronics circuit technique is to achieve circuit formation costs below those of conventional circuit component assembly costs, coupled with the previously defined size, weight, and reliability improvements. If these objectives can be satisfied, then microelectronics circuit formation techniques can be used on their own merits, and not just as an ultimate solution of a previously insoluble problem or as a current technological "fad."

Microelectronics is the formation and implicit interconnection of various values of resistance, capacitance, and inductance with active elements in the semiconductor family, such as transistors and diodes, to produce a complete and functioning electronic circuit. The Sylvania microelectronics program is intended to perform research, development, and pilot production for laboratory-developed advanced circuit-formation technologies, which may include the mounting in place very small and unique standard electronic components.

The basic element on which the circuit is formed is the microcircuit wafer. Figure 1 illustrates two of the many possible configurations with which we have worked. The wafer illustrated on the left is a nominal 0.5 in. square and contains 2 capacitors, 6 resistors, 2 diodes, and 2 transistors, while the one on the right, a nominal 1 in. square, has 9 capacitors, 19 resistors, 3 diodes, and 7 transistors. Both designs are presently in pilot fabrication at Sylvania, and each has its own particular justification for size and circuit complexity for application to microelectronics. Obviously, where use is made of a large wafer size external circuit interconnections are minimized, since more circuit function can be placed and

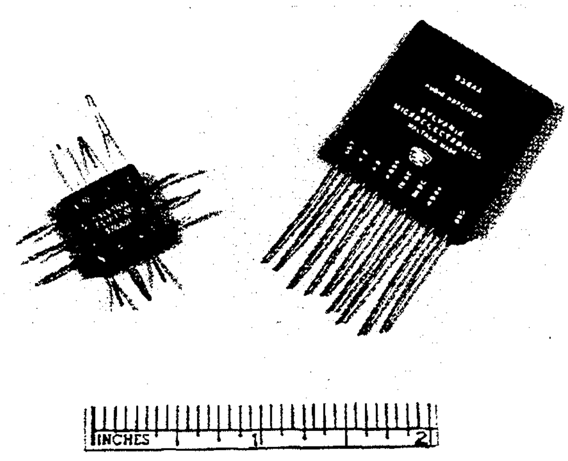

Fig. 1. Sylvania microelectronic circuit wafers.

interconnected on a single surface as part of the circuit formation process. However, the particular circuit and system requirements of each application will dictate what the substrate size ought to be.

Where high circuit heat density—and therefore a heat removal problem—is found to exist, heat sinking is more easily performed if we form the circuit on only a single face of the ceramic wafer, since we can then directly heat sink to the back surface of the ceramic wafer. The heat transfer characteristics of high-alumina material are over 30 times better than those of the commonly used glass substrate.

Individual circuit wafers, after formation, testing, and protection, can be stacked to use height as the third dimension in achieving high-density microelectronic circuits with integral interconnection. This aspect has so far been accomplished only with the smaller wafer. One factor that must be considered in this technique is the cost of replaceable or throw-away circuit assemblies, which must be determined by the ultimate application of the system being constructed. It is significant to note that the fabrication and testing equipment for the small and the large wafer is not only interchangeable, but in many cases identical.

The wafer itself may be considered as the floor in a building. It supports electrical circuitry in place of furniture and is itself supported for mechanical reasons. A wafer must have the following characteristics: chemical inertness, to withstand circuit process chemical preparations; good electrical insulating qualities; rigidity and stability, to permit circuitry to be formed directly on its surface or attached to its surface; physical or structural strength, to withstand handling and assembling operations; high thermal conductivity; smooth surface finish; and reasonable cost. The material we have selected for our microcircuit wafer is a high-purity (96–98%) alumina, ground to a surface finish of 20 μin. rms or smoother.

The wafer is the structural plane on which circuit elements are formed and electronic components are mounted. Not only can microminiaturized or "state of the art" very small components be weld-attached to conductors formed on this ceramic surface, but vacuum components can be deposited as thin film circuits, or attached as silicon-base integrated circuits to this same surface, to permit the intermingling of different forms of circuit elements now referred to as microelectronics. The circuit element or circuit-forming technique which today is found in a research laboratory will tomorrow be in advanced development and only a step removed from common use. The substrate wafer must accept this continuous evolution and change, and possess the basic characteristics and flexibility to accept techniques most applicable to forming the end-resulting circuit without compromise and without being readily made obsolete.

To demonstrate some of our techniques in detail, we must explain some of the processes and equipments which we employ in forming thin-film microcircuits with attached parts.

After cleaning (by a solvent-acid cycle), the wafers are ready to undergo the first step in their conversion to an electrical circuit. This operation is the application of conductor lines and weld pad areas to the wafer, to permit the welding of such components as transistors and diodes during subsequent operations. This

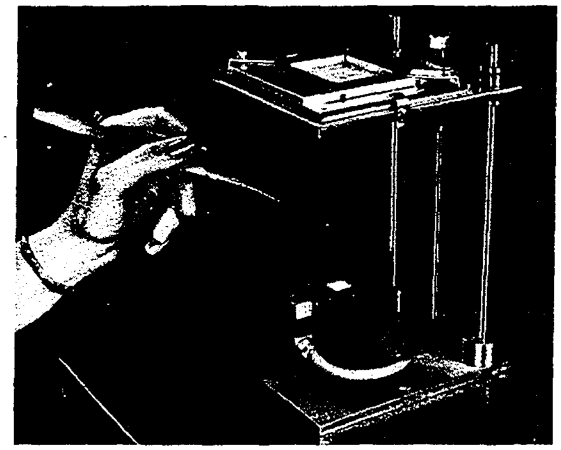

Fig. 2. Silk-screen machine.

step uses the silk-screening technique of applying a silver-loaded glass frit to the ceramic wafer (substrate). The lines currently being produced in this manner are as fine as 0.010 in. in width.

Figure 2 shows the machines used to perform the silk-screen operation. They are air-cylinder-actuated, both to reduce operator fatigue and to assist in precision coordination of the silk-screening operation. The alignment of the silk screen to the substrate is accomplished by pre-aligning the screen to a master pin position by optical means. Figure 3 shows an optical alignment fixture. It provides for X, Y, and rotary positioning, to allow the operator to align and position the mounted silk screen to the pin-positioned frame carrier. An optical head is mounted above a through-the-back illuminated optical flat, containing a master pattern, to which the silk screen is to be aligned. This precise alignment pattern is carried throughout the manufacturing process, not only in silk screens but also in vacuum evaporation masks.

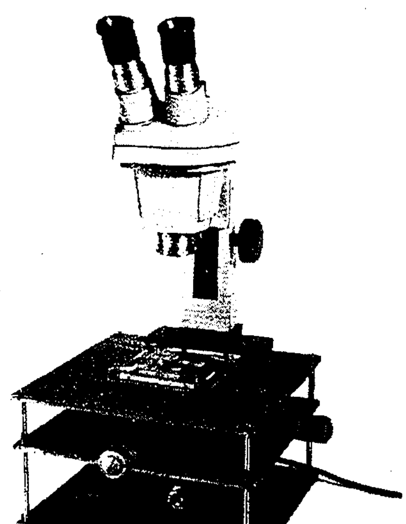

Fig. 3. Silk-screen optical alignment fixture.

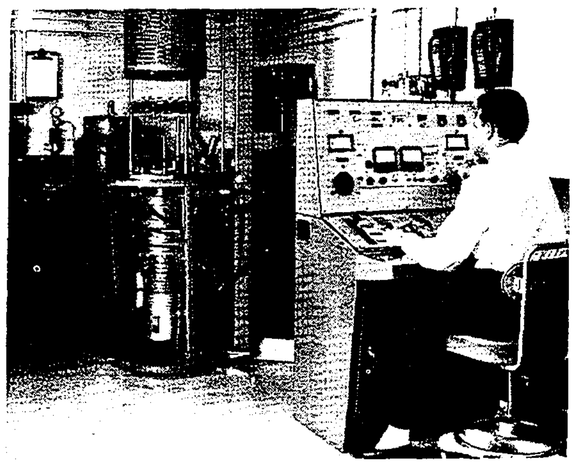

Fig. 4. Vacuum evaporator.

Precise alignment throughout the process has a direct bearing upon the ability to produce dense circuitry. The more accurately the various process steps can be maintained with respect to each other, the closer conductor lines may be positioned with respect to each other and the smaller may be the land areas reserved for overlaying interconnections and circuit elements in the various process steps. The conductors, after having been applied to the ceramic, are fired at 760°C.

It is to be noted that the sequence of wafer (substrate) processing is dictated primarily by the ability of each operation to withstand the subsequent ones. For example, the fired silver conductors can more than withstand the 350°C temperature to which they are next subjected in the vacuum evaporator, while the nichrome

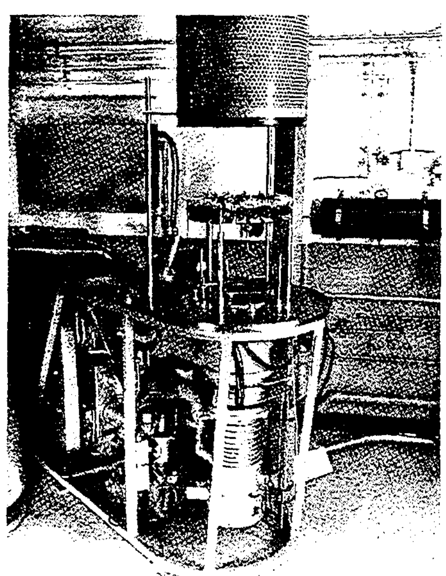

Fig. 5. Vacuum evaporator pumping and evaporating sections.

resistors which are vacuum deposited will not withstand the 760°C temperature of conductor firing.

At present, the next operation performed in our pilot fabrication facility, that of vacuum deposition, consists in evaporating high-stability nichrome resistors. Although more advanced techniques are to be added shortly, this paper is only concerned with the present method of fabrication.

The vacuum evaporator shown in Fig. 4 has two major parts. Figure 5 illustrates the pumping and evaporating portion, while Fig. 6 is the complete remote control console. Both were designed by us to fulfill the requirements of a high-speed, high-vacuum evaporator, capable of being operated by personnel with little knowledge in the field of vacuum evaporators. Our knowledge that improvements, in the form of high-dielectric and resistivity films, will shortly be added when they are released from the development area was an additional complicating factor in the design. These improvements will result in equipment changes varying in complexity from a minor tooling revision to the incorporation of electron beam deposition with its allied monitoring systems, and the incorporation of a system to permit repetitive multiple evaporations without opening the evacuated area to the atmosphere.

A schematic diagram of the pumping system is shown in Fig. 7; it is built around an oil diffusion pump capable of pumping 1440 liters/sec. It is what is presently referred to as a high-speed 6-in. pump. The classical vacuum equipment design of including both roughing and holding mechanical pumps is used. The decision to include the holding pump was based on the desire to obtain greater versatility and the assurance of being capable of maintaining a fabrication sequence in case of a roughing pump failure.

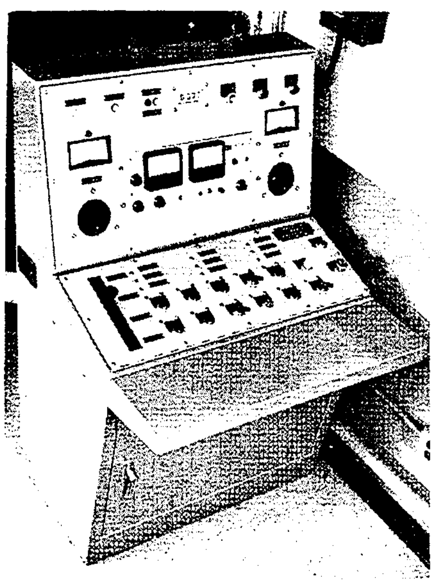

Fig. 6. Vacuum evaporator remote control console.

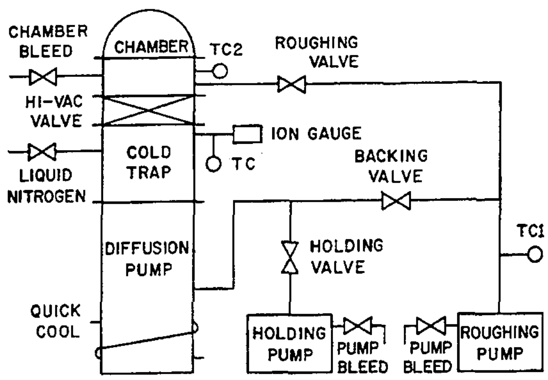

Fig. 7. Schematic of high-vacuum evaporation system.

A square steel tube frame was used to support all but the mechanical pumps, which are floor-mounted to isolate their vibration from the evaporator. No enclosures are used, and therefore maintenance accessibility is excellent. The control console is connected to the pumping station by wires running through electrical conduit. This permitted individual fabrication, assembly, and checkout of the two major equipment subassemblies.

Operation control is accomplished manually via panel-mounted oiltight lever switches. Standard hardware was used to reduce cost and permit minimum maintenance time in case of equipment failure.

The operational sequence is provided to the operator by means of a sliding plate. Four positions of this plate cover the four phases of the operational sequence. In the design of the controls of the console, we have semiautomated the operation of the evaporator while displaying full information on the status of the function of the equipment.

The present evaporator is designed to accept twenty-four 0.5-in. tabbed wafers of the type shown in Fig. 8, or any square or rectangular wafer up to $1\frac{1}{8}$ in. on a side.

The vacuum-deposited nichrome film resistors are checked to verify their value. A system of both visual and audible readings is used to indicate proper resistor value. Adjustment when necessary is performed by means of a powered surface abrader to achieve tolerances to 2%. After aging at 180°C, the resistors are again checked for value.

In the next operation, capacitors and semiconductors are capacitor-discharge mounted to the conductors previously screened and fired to the wafer. The actual sequence of mounting is based on two factors:

1. Relative cost per component, the least expensive first.
2. Grouping of components with identical lead material to minimize changes in the weld schedules.

To permit rapid positioning of the welding electrodes, the welding head has been mounted on a stand which has X-Y-Z motion. The X-Y motions are accomplished by use of a joy stick control whereas the Z motion is accomplished by use of a lever controlled by the hand which is not using the joy stick.

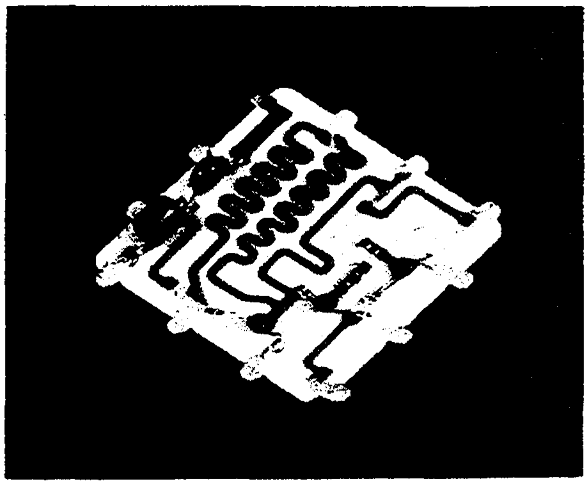

Fig. 8. One-half-inch tabbed wafer.

Tension gages mounted on the head which is companion to that mounting the welder are employed to check the bond strength of each weld.

Mounted components are electrically checked prior to being terminated on the wafer, to assure high product yield of completed wafers. Here again an area is encountered which, although not foreign to component testing, is unique in the provisions which have to be made to prevent damaging the minute articles under test. The rack and pinion action found in microscope focusing blocks has proved to be lightly suited to this task. A pressure pad which applies force to the component part's leads, and thereby maintains electrical continuity between the leads and a contact plate, enables test instrumentation to be connected without damaging the item under test.

Adaptations of this basic equipment have been applied to the testing of capacitor chips both prior to lead mounting and subsequent to the welding of these leads to the chip, and to the testing of very small diodes and transistors. Recently completed circuit wafers have been tested by fixtures only slightly modified from this basic design. Figure 9 illustrates these fixtures, along with items tested on each.

Upon completion of component mounting and termination, the virtually complete wafers are checked electrically and are then prepared for encapsulation. The initial step in the encapsulation process is the coating of all circuit elements with a conformal coating of flexible silicone. This coating is approximately 0.002 in. thick. Its function is to act as a resilient protective barrier against the thermal expansion and contraction of the epoxy coating applied in the following operation. Curing of the conformal coating is accomplished at 85°C. The epoxy coating which provides both final protection and the exterior shape is molded and then cured at 85°C. (After curing, the epoxy is good for 125°C continuous duty.) Final steps in the production are the application of termination and identification information

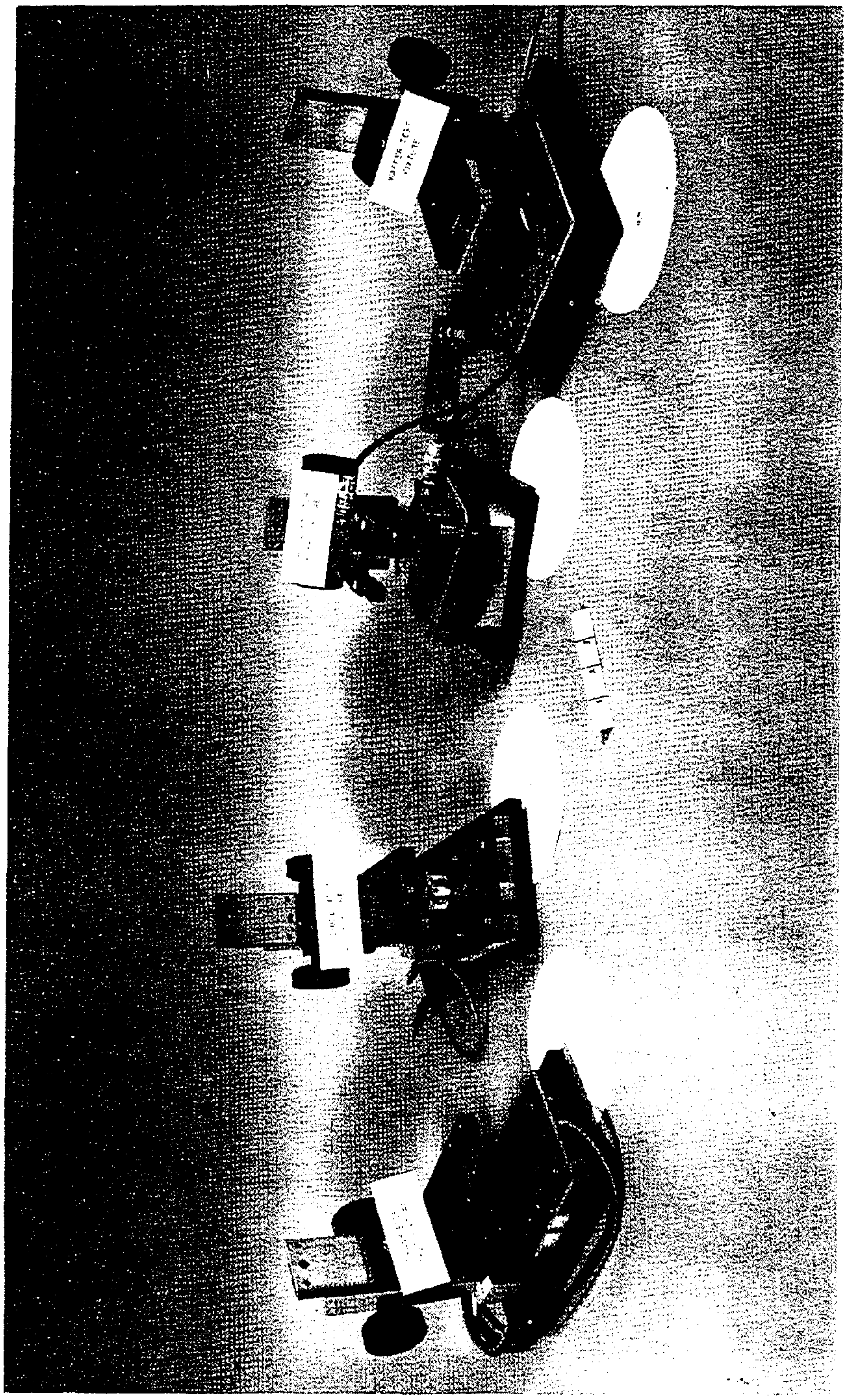

Fig. 9. Focusing block test fixture.

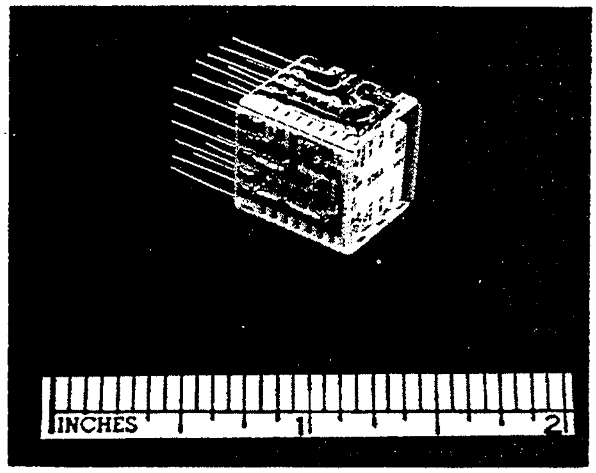

Fig. 10. Complete microelectronic module.

by silk screening, followed by final electrical circuit test prior to packaging for shipment.

Figure 10 illustrates a complete microelectronic module composed of 5 tabbed wafers. The sample shown contains 2 flip-flops, 2 gates, and 2 line drivers. The module is 0.5 in. on a side and 0.53 in. high, with a component density greater than 570,000 parts/ft^3. Interconnections are made between wafers by conductor lines silk screened and fired to the alumina side interconnection boards in identically the same way as the conductors were formed on the ceramic wafers. Flow soldering with silver-loaded lead–tin solder completes the interconnection process. The wafers, leadout pins, and interconnection boards are assembled on the jig shown in Fig. 11. The module is coated, marked, and once again electrically checked, and is then ready for shipment.

The objective of this paper has been to show that packaging, as we now speak of it, is taking new and more advanced directions in order to produce microelectronic circuitry. To accomplish this at Sylvania, it has been necessary to devise

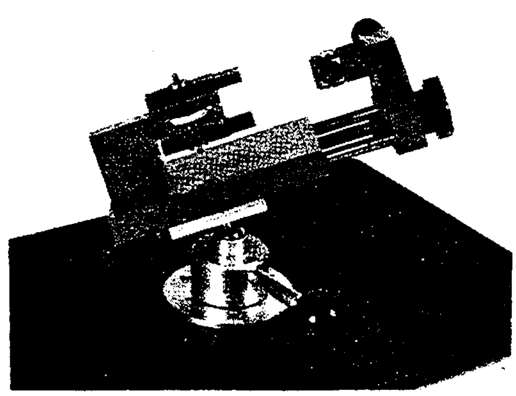

Fig. 11. Microelectronic module assembly fixture.

and incorporate unique mechanical and optical aids which permit the efficient physical manipulation and formation of very small electronic elements and components with precise and highly reliable termination, and to employ them in microcircuit formation and packaging.

ACKNOWLEDGMENT

The work and development described in this paper are funded by Sylvania Electric Products, Inc., a subsidiary of General Telephone & Electronics Corporation; a number of patents are pending on these developments.

DISCUSSION

Q. (Joe Walentine, RCA Labs., Princeton, N.J.) In the silk-screening operation, what type of screen is used, what mesh is it, and is it stainless or silk screen?

A. It is a cloth screen (Nitex), mesh number 305, which was the finest available a year and a half ago when we first required it.

Q. Though you say ten thousandths wide in your paper, how fine a line have you actually silk-screened with any kind of resolution and without fuzzy edges?

A. With a trained operator and controlled viscosity of the frit, you can get as fine a width as three thousandths, but it is nothing that I would recommend as a reliable thing. I haven't mentioned our Advanced Development work now actually vacuum evaporating the conductors in place. The problem here is of mask changing (multiple) in the vacuum evaporator.

Q. What overcoat material do you use on the piece prior to encapsulation? Is it similar to RTV?

A. It is a flexible silicone coating, designated Dow Corning DC-271 diluted with MEK; it prevents tearing the leads from the welded position during curing of the epoxy. It does not resemble RTV.

Q. (K. A. Allebach, Nortronics, Palos Verdes, Calif.) I understand you vacuum-deposit resistors, and silk-screen conductors. How do you make capacitors?

A. The capacitors are coated with a silver frit (DuPont 7713) and then fired. The chip capacitors are cut from purchased titanate discs, with a number of blades on an ultrasonic tool so that we get first one dimension, then we rotate the disc and cut the other dimension.

Q. (Amp, Inc., Harrisburg, Pa.) In the welding of the small components to the piece itself, do you use resistance welding and, if so, do both the electrodes come down from the top? Also, do you have trouble with the heat lifting the deposition from the little substrates?

A. We are, indeed, coming down with two electrodes from the top, but we do not have problems with anything lifting. There was some problem with some of the fine lines of the small transistors to get the proper weld schedule because of the almost nonexistent amount of power. Originally we had planned on thermal compression bonding and that is the reason that there is a thermal compression bonding position on the head. However, we are now welding completely.

Q. (Don Schnorr, RCA, Camden, N.J.) I am interested in the measuring technique you used for measuring the resistance of your nichrome resistor. You mention that you do it electrically and also optically. Do you have some sort of optical arrangement for determining the thickness of the film?

A. I didn't intend to indicate that we were measuring the thickness of the resistance film on this pilot line, but we were doing it in the laboratory area. We are actually measuring the thickness of the resistors by coming in with probes to the land areas of the resistors, rather than going directly to the resistors. All of the resistors are terminated at land positions, so that we can take into consideration the tolerance overlay of the two dimensions. Also, notice that in some places we have land areas in the center of straight resistors. We do this to allow us to hold the masks together on the vacuum-deposition fixture. In other words, if we have too long a resistor lead it is just a big wiggly line and it would drop out, so we leave a pad area and silk-screen a conductor pad in that particular place.

Q. You mention that you abraze these resistors to change the value upward. Do you use one of the air abrasive guns or is it a mechanical method?

A. It is a mechanical method.

Q. (Vince Galati, System Development Corporation, Santa Monica, Calif.) Did I understand you to say that you built this console for your vacuum equipment yourself?

A. That is correct.

Q. I would like to compliment you on the design of the console, which you said you built yourself, but I would also like to say that it was most unfortunate that you were unable to get one of these cabinets to suit your needs on the market for $250.00.

A. We purchased the cabinet alone from Hoffman, Anoka, Minn., but within the cabinet we built the controls and displays which make it a console.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) I notice that in your resistor patterns the looping was round as opposed to the normal right-angle bend. What is the advantage of producing your resistor pattern in this manner?

A. If you use a right-angle bend you lose resistance. The values of these resistors are based upon the length of their leads and the material deposition in terms of ohms per square. A right-angle bend does not give the full total length. In other words, the angle is such that you will only actually obtain half of the resistance of that length.

Q. I noticed your sequence of operation was to silk-screen first and then vacuum-deposit. Now, in the silk screening the frit is considerably thicker than the film that you are going to deposit. Am I correct in assuming that?

A. If you measure it in angstroms, yes.

Q. How do you get the interface from the film to the frit? Do you actually have to creep up the third dimension of this frit?

A. This is not the problem so much as preventing the vacuum-deposited materials from creeping underneath the mask. The biggest problem for fineline definition is to keep the substrate in physical contact with the evaporant mask. The system here is that in the vacuum evaporator the mask is placed below and the substrate is mounted above, and then we actually apply a heated weight. This holds the substrate to the mask in physical contact. If this isn't done, the result is a shadowing effect. If you have ever done any spray painting you know what I mean. The mask, instead of blocking the evaporant off straight as it would with rays of light, without the physical contact would permit the vapor to come up behind.

Q. What prevents you from changing the sequence of the process?

A. The temperature for the firing and curing of the frit is higher than that in the vacuum evaporator. The nichrome resistors will not withstand the firing temperature required for firing silver. Specific temperatures are given in the paper.

Q. (Byron Smith, Martin-Marietta, Baltimore, Md.) Is there any reason why you didn't go to vacuum-deposition of the conductors as long as you were doing so with the resistors?

A. At the present time we have a fixture in the *R/D* area which is a multiple mask positioner, by means of which conductor lines can be evaporated, sources and mask changed, then evaporation repeated. There is a mechanical problem of getting motions into a vacuum system and changing the evaporant source. The first step is a simple filament heating. The present plan is to go to electron beam deposition, focusing an electron beam onto a source. You have got to walk before you can run, and we felt it would be better to use the processes described in the paper for pilot production, and be able to produce a product and handle it and work with it rather than wait until we could get all of the other processes debugged.

Q. (John Rivera, RCA, Somerville, Mass.) What led you to select thermal compression bonding first as a technique for making connectors and then go into welding, and could you also tell us a little bit about the advantages and disadvantages?

A. Thermal compression bonding was considered because of our familiarity with it from our semiconductor activity. There were fixtures that we could readily procure for thermal compression bonding, such as the machine illustrated, which has a thermal compression bonding head but has never been used that way. By the time the machine came in, we had perfected the welding techniques. The reason that we thought of using it was the trouble that some of the semiconductor people had in putting leads onto their chips directly. The disadvantages of thermal compression bonding over welding are the length of time required in a one-at-a-time process and the very high breakage rate of the tip on the thermal compression bonder. Also, using a straight welder we can eliminate such problems as different fixtures and different tooling.

Q. (Bob Bender, Hughes Aircraft, Newport Beach, Calif.) In earlier presentations Gerald Selvin of Sylvania described a glass hat sealing technique wherein you sealed a glass lid through a glass-to-ceramic seal. Has this approach been abandoned and if so could you tell me why?

A. The original approach, and the people here in the audience I'm afraid don't know it, was to use transistors which were unsealed. We were using straight transistor chips, having no protection. When we changed to protected transistors which are themselves passivated, there was no requirement to protect the transistors as such. And, apparently, from the tests that have been run no protection is required as far as our resistors are concerned. Complete sealing, however, has not been discarded altogether, but this is on a systems packaging approach rather than on a circuit wafer-type approach.

Q. (Harry Stuy, Hoffman Electronics, El Monte, Calif.) What kind of insulation do you use on the lead-in wires to heating elements in the vacuum chamber?

A. Glass.

Q. (Anthony Fedewitz, Grayhill Moldtronics, Cedar Grove, N.J.) The encapsulation technique, about which you have spoken, is apparently of a prototype nature for short quantity runs. Have you given any thought as to how you would have solved this problem of encapsulation for production?

A. If there were a market for wafers as such we would perhaps continue with the prototype method so that we could put more circuitry on the wafer. But for production, the problem is to make a thin enough plastic molding into which we can pour our encapsulant. We have requested from vendors a ring 0.010 in. wide to permit the encapsulation being done about 0.065 in. high, but thus far have had no satisfaction. So we made up some simple molds and are just pouring the epoxy in.

NO

Microelectronics* and Megaheadaches

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This paper deals with the techniques of microelectronics and associated problems. Thin-film technologies are reviewed and a discussion is included concerning the program to develop a thin-film integrated circuit technology, currently in progress at the Electronic Sciences Laboratory at Lockheed.

THE ELECTRONICS industry is in a constant state of evolution. The conceptual technology of the industry is rapidly changing and moving steadily toward the design and fabrication of smaller, more sophisticated electronic systems. To packaging engineers, who a few years ago utilized only the hand-wired metal chassis, this industrial evolution may seem to be progressing at an alarming rate. The jargon of one concept is barely learned, when another concept—complete with its own new jargon—emerges from the laboratory. The headaches in this evolution are not solely limited to communications among professional people who glamorize their new electronic components, but also include the design and fabrication interrelationships of these new technologies.

Many electronic packaging engineers will soon be designing microminiature electronic packages. The designer must understand the interrelation between materials, processes, configurations, and product performances that are so much more critical in these new technologies. These interrelations have been very apparent in the design and fabrication operations of the Electronic Sciences Laboratory at LMSC during the development of a thin-film integrated circuit technology.

THIN-FILM TECHNOLOGIES

Thin-film technologies have been proposed for the design and fabrication of electronic systems to meet the requirements of improved reliability, simplified producibility, reduction of physical parameters, and economy. It has been assumed that thin-film technologies are related to or desirable only in microminiaturization applications; actually, such technologies are applicable to a full range of power levels and circuit types compatible with those parameters of component-type

* The AIEE/IRE recommends using the term *microsystems electronics* (MSE) to refer to that electronic art which applies to the realization of extremely small electronic systems.

assemblies. Indeed, size reduction is an important by-product of the application of thin-film technologies to improve reliability of electronic systems.

Thin-film integrated circuits (Fig. 1) are fabricated from a patterned area interrelation of thin films of electronic materials on a structural base material. These circuits perform functions analogous to those of electronic circuits assembled from basic pigtailed component parts. Thin-film integrated circuits are fabricated from a wide range of conductive, resistive, semiconductive, dielectric, and magnetic materials, as well as from multilayered complex combinations of such materials. The assembly of only the required electronic materials in the circuit or function pattern results in size reduction for a given circuit function in comparison with a component assembly, due to the elimination of the redundancy of structural and connective materials common to component part assemblies.

Thin-film technologies have a significant role in electronics. Such technologies place the control of design and fabrication in the hands of the systems engineer, who can specify and then achieve the performance and configuration of the circuit. Hybrid circuits utilizing thin-film integrated circuits, coupled with other packaging techniques, may be used wherever it is to the designer's advantage to use them. Thin-film technologies meet the requirements of reliability under a wide range of environmental conditions because of the availability of many materials and the choice of structure and pattern. Production aspects are unique in that a circuit pattern is reproducible in practically limitless quantities from a single photographic pattern formation tool. Costs vary widely depending upon the fabrication processes; in general, however, they appear to be less than the cost of equivalent component assemblies. Size and weight reductions are important advantages of the thin-film technologies, but they may not be achieved unless the power level of the

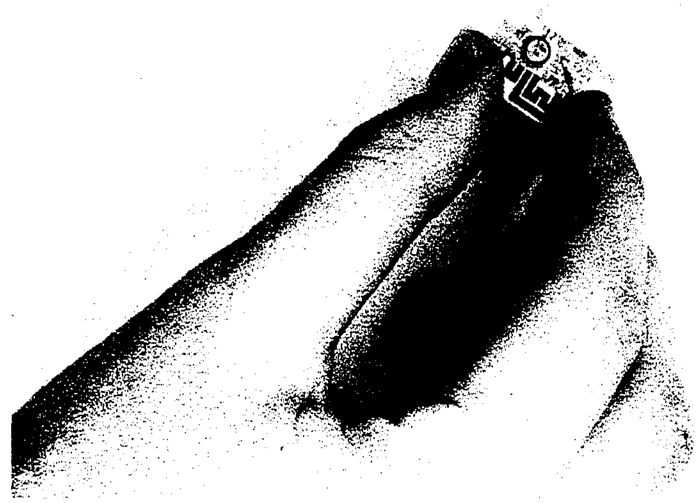

Fig. 1. Typical thin-film integrated circuit (low-power flip-flop).

component is reduced to match the thermal characteristics of the structure. The capability of thin-film integrated circuits to meet the overall requirements of electronics is found in the interrelationship of processes, materials, and design limits.

SINGLE-METALS TECHNOLOGY

The extreme environmental requirements of missile and space systems established the need for highly stable electronic materials. Research studies have shown that refractory metals and oxides were potentially capable of meeting the application requirements.

Refractory materials are considered to be those with melting points in excess of 1500°C. (In most cases, this value is in excess of 2000°C.) In addition to metals such as tungsten, tantalum, molybdenum, zirconium, hafnium, and titanium, this category includes many compounds such as lanthanides, actinides, and some alkaline metals. In addition to the simple compounds, many double compounds have electronic properties; double oxides of titanium and zirconium, for example, have well-known dielectric properties. The refractory oxides, because of their wide range of electrical properties, are perhaps the most interesting of the refractory materials. These oxides encompass a range of compounds—from extreme insulators to near-metallic materials. Oxides in the maximum oxidation state for a given metal are very high-resistivity materials. Those in the minimum oxidation state are near-metallic in properties. Intermediate oxides frequently display semiconductive properties.

The *Microsystems Electronics* (MSE) *Program* is concerned with the development of chemical processes for the fabrication of thin-film and solid-state integrated circuits using the titanium oxide system. This thin-film technology has advanced to an experimental pilot-plant phase for the fabrication of integrated circuits.

Fabrication of a thin-film titanium circuit (shown in Fig. 2) starts with a molten-salt process that results in the complete coating of an inorganic substrate with a thick film of very pure titanium metal. After cleaning, a pattern of copper or other conductive material is electroplated onto the metallized substrate to produce termination areas or interconnection tabs. The circuit pattern is then fabricated from the metallized substrate by photoetching processes. Later in the process, external ribbon leads are fastened to the metallized pads on the substrate by furnace-brazing or soldering.

The next step in the fabrication of the thin-film circuit is the conversion of selected areas of the continuous circuit pattern into a resistive or dielectric material. For both of these materials, an anodic process is used in which the electrolyte and the electrical process parameters determined the resulting material parameters. A jig or mask which restricts the electrolytes to selected areas is used. An important part of this conversion process is a technique for the measurement of the electrical parameter: resistance, capacitance, or dissipation factor, during the anodic process. This type of process control is termed *dynamic testing*. Resistances are individually trimmed to precise values by further anodizing or mechanical operations.

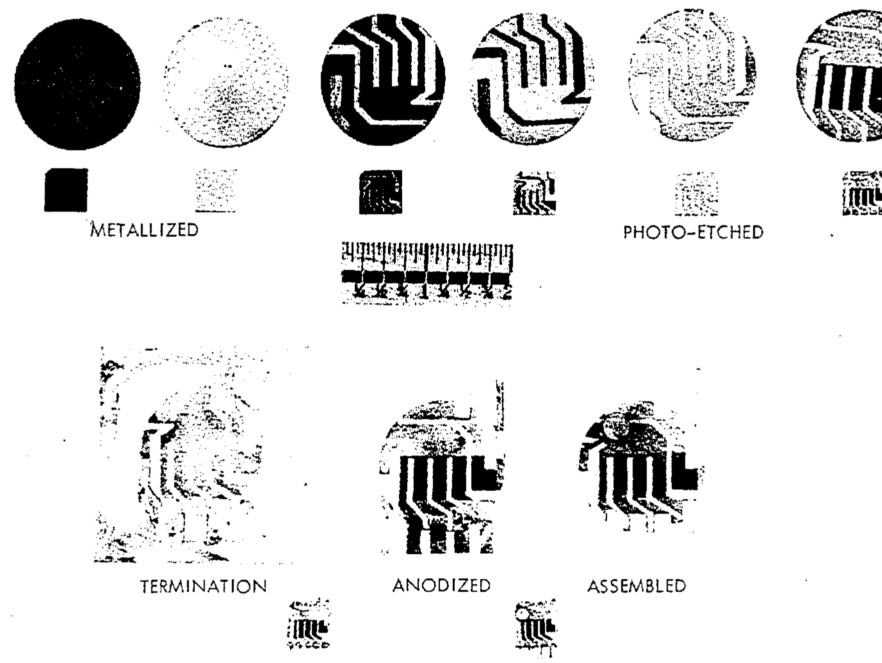

Fig. 2. Titanium thin-film circuit fabrication.

Capacitors are then formed by adding a counterelectrode to the dielectric pattern and mechanically adjusting as required.

After the fabrication process, the active devices are assembled to the thin-film circuit by spot-welding, thermal compression bonding, or soldering; the titanium thin-film integrated circuit is ready for use.

Individual electronic functions may be fabricated in this manner for experimental system development. However, to utilize the full potential of thin-film integrated circuits, a more complex assembly of circuits may be fabricated to further reduce the number of external interconnections required in the system.

FILM CHARACTERISTICS

The characteristics of titanium-film resistors prepared by these chemical processes are illustrated in Figs. 3 and 4. The temperature coefficient of resistivity varies with the material thickness, from $+120$ ppm/°C at 50 ohms per square to -100 ppm/°C at 2000 ohms per square. A zero temperature coefficient exists at approximately 1300 ohms per square. Extensive life-load-environmental testing has shown that the resistance changes approximately 0.6% per 1000 hr for all combinations of environments.

The characteristics of the titanium dioxide dielectric are shown in Fig. 5. The capacity is 0.01 mf/cm^2, the dissipation factor is less than 1% and the leakage

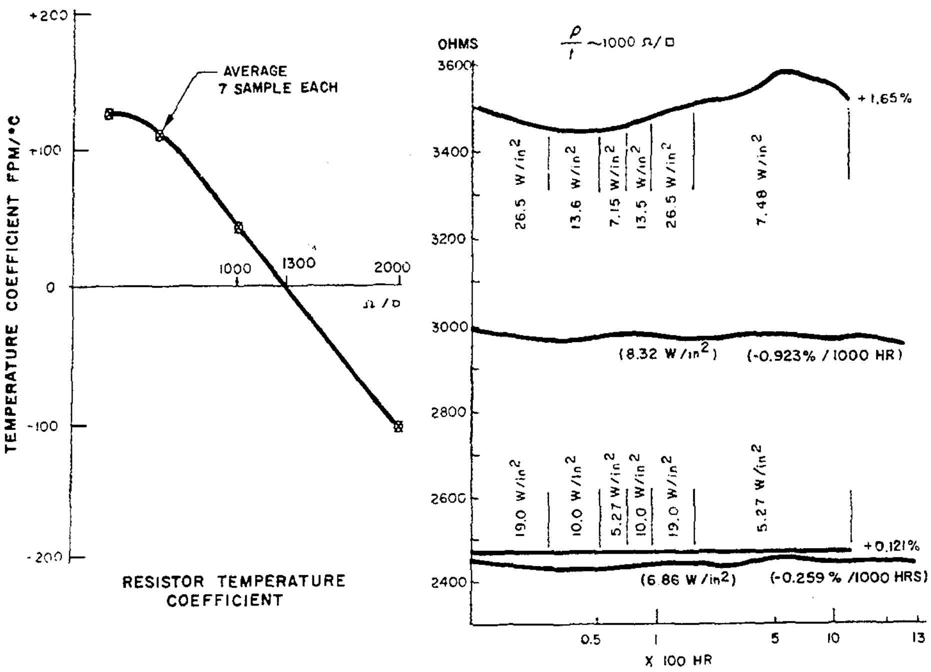

Fig. 3. Resistive characteristics.

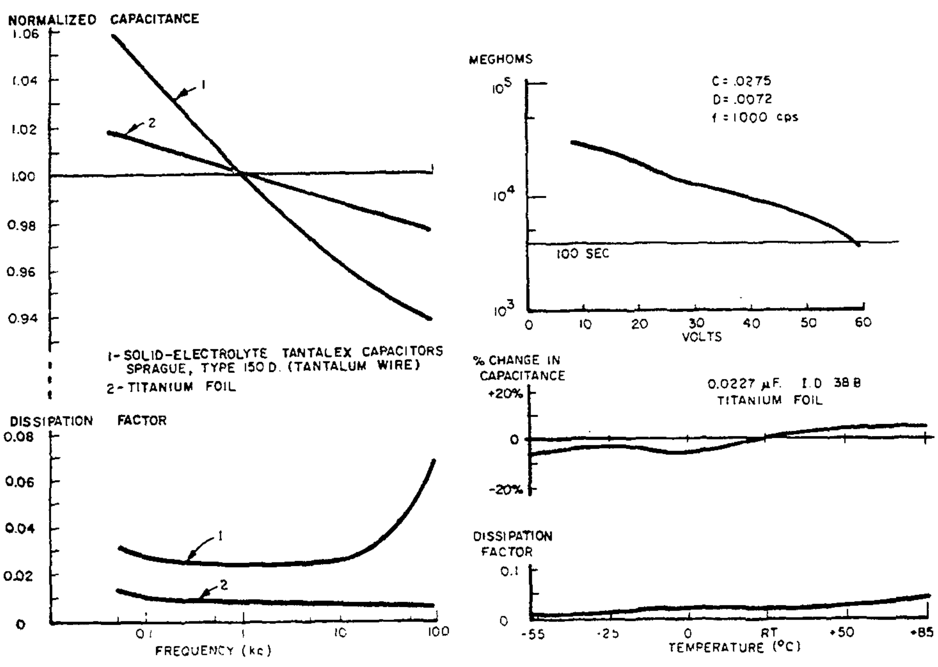

Fig. 4. Dielectric characteristics.

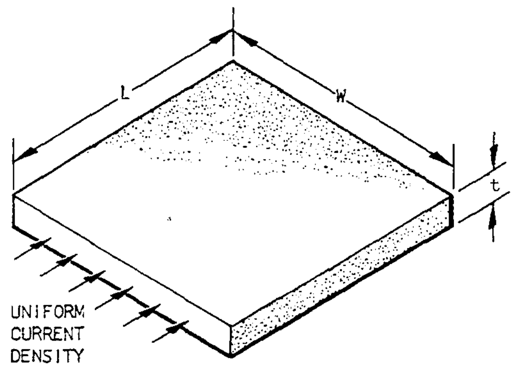

Fig. 5. Resistance of a solid.

resistance exceeds 2×10^4 megohms/cm^2 at 50 v dc. The change in capacitance and dissipation factor with frequency is small and the temperature characteristics are approximately 800 ppm/°C.

MORPHOLOGY*

Designing a thin-film integrated circuit is similar to designing a printed circuit board. However, more constraints are imposed upon the film circuit, and the procedure is more difficult. The constraints arise because of geometric principles inherent in film circuitry and because of certain fabrication requirements peculiar to the thin-film process.

Resistance

Resistivity of the film is expressed as *ohms per square*. This terminology is derived from the following basic equation for the resistance of a rectangular solid (see Fig. 5).

$$R = \rho\left(\frac{L}{tW}\right) \tag{1}$$

where R is the total resistance of the solid in ohms, ρ is the resistivity—a constant of the material, L is the length, W is the width, and t is the thickness.

The above equation may be written

$$R = \frac{\rho}{t}\left(\frac{L}{W}\right)$$

If L is equal to W (as for a square pattern),

$$R = \left(\frac{\rho}{t}\right)\left(\frac{W}{W}\right)\left(\frac{\rho}{t}\right)$$

* Morphology: The structural characterization of an electronic component in which the areas or patterns of resistive, conductive, dielectric, and active materials in or on the surface of the structure can be identified in a one-to-one correspondence with component parts assembled to perform an equivalent function.

The ratio (W/W) is always unity and does not depend upon the actual size of W. Thus, for square shapes of any size, the resistance is always (ρ/t). In practice, ρ and t are not measured separately, but their ratio is determined by a simple electrical test. If we let $r = \rho/t$ be the unit of resistivity of a film, or sheet resistance, the total resistance of any rectangular shape is

$$R = r\left(\frac{L}{W}\right) \tag{2}$$

where L/W is the aspect ratio [length/width] of the shape.

Pattern Shape

Equation (2) is valid only if the film properties are uniform and the current density is uniform over the width of the pattern. Uniformity of properties is dependent on process control and is the responsibility of the fabricator. Current density is influenced by circuit layout and is controlled by the designer.

Resistor patterns are typically made as wide as possible, within the size limitations of the package to minimize tolerance problems. The conduction paths are usually narrower to save space. It is necessary to provide a transition section between the narrow conductors and the wider resistors (Fig. 6).

The transition section distributes the current evenly across the resistor and enables the resistance values to be predicted from pattern geometry. The same requirement of uniform current distribution makes it undesirable to design resistors with aspect ratios less than 1.0.

The long path of the resistor shown in Fig. 7a helps to even out irregularities which may exist in the entering current. The path through resistor b is too short to allow redistribution of current density within the resistor. Short, wide resistance patterns such as b may behave unpredictably when connected to other devices in a circuit.

The shapes shown in Fig. 8 may be used to permit the pattern to go around corners.

A nonuniform current density will exist in the region of the bend, and Eq. (2) is not valid. The principles of electric field theory must be used to compute the effective resistance value of such a pattern. The effect of the bend must be considered for a relatively short resistor; however, for a long resistor, the effect of the bends can be neglected. The long sides of the loops contribute more to the total resistance than do the bends. It is preferable to have no bends in the resistor area

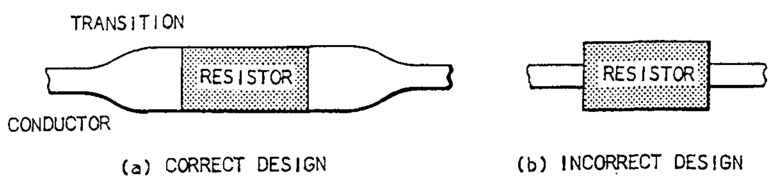

Fig. 6. Transition section.

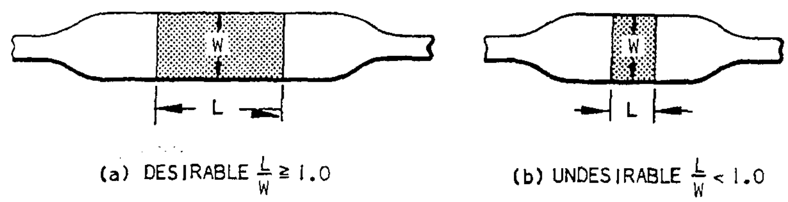

Fig. 7. Aspect ratio.

where possible. Straight lines interconnected by shorting pads may be used for higher resistances.

Line Width and Tolerance

Accuracy of resistance pattern length and width is very important. A film pattern requires closer tolerance than does a printed-wiring board, because the electrical properties of the film circuit depend upon pattern geometry.

The conventional line-width tolerance for printed circuit fabrication is ± 0.005 in. If this tolerance were applied to the narrow (0.030-in.) lines required for high-value resistors, the error due to line width alone would be:

$$\text{Error} = \frac{0.005}{0.030} \times 100 = 16.7\%$$

To achieve accurate resistance values, the pattern tolerance should be no more than $0 \pm .001$ to 0.002 in., preferably even smaller. Close tolerances require large-scale art work (20– or 40–1), accurate camera reduction, and extra care in all fabrication steps.

The total error due to pattern geometry is the sum of errors in both the width and the length. Thus, in the worst case

$$\text{Percent error in } R = 100\left(\frac{L}{L} + \frac{W}{W}\right) \tag{3}$$

If the absolute errors in both dimensions are equal to the same value e (where e is the specified tolerance)

$$\text{Percent error in } R = 100e\left(\frac{1}{L} + \frac{1}{W}\right) \tag{4}$$

and division by W yields

$$\text{Percent error in } R = 100\frac{e}{W}\left(\frac{1}{L/W} + 1\right) \tag{5}$$

Fig. 8. Pattern bends.

It is apparent that if the aspect ratio L/W is much greater than 1.0, the term $1/(L/W)$ becomes insignificant. The error in resistance is then due primarily to the width tolerance.

The tolerances in Table I represent a headache because, from a power standpoint, smaller lines of resistance patterns could be used, but a better pattern formation is required.

Pilot Plant Development

The basic techniques and processes for thin-film production were developed during the research phase. Applying them to pilot-line production presented the initial problem. (See Fig. 9 for process details.) In the research phase, resistors had been made by simply masking the resistor area with 0.250-in.-wide tape during the titanium etching process. This method produced lines of sufficient accuracy for process development, but did not provide sufficient accuracy for more sophisticated circuitry to be fabricated on the pilot line. Therefore, photoetch techniques similar to those used in producing printed circuits were introduced. These techniques, slightly modified, were very efficient in producing high-resolution pattern areas. The existing printed circuit technique was modified to gain additional chemical resistance to some of the etchants used in the process. It was also decided that a thin copper plating to provide additional protection from the etchants and attachment points for leads and active components would be highly desirable. This decision proved to be another headache: Plating to titanium is fairly difficult and the bond between the parent metal and the plate is relatively weak—sufficiently weak, in fact, that anything attached to a plated pad easily separates the pad from the parent metal when a small force is applied to it. To alleviate this problem, another step was introduced—the diffusion of copper to titanium.

At first, diffusion was attempted using an argon atmosphere furnace. Diffusion in an argon atmosphere, however, was uncertain and there was a tendency to oxidize titanium surfaces or, in some instances, to completely evaporate them. The titanium film removed impurities from the argon rather than being protected by it. To eliminate the high reject rate resulting from this process, other diffusion

TABLE I

Suggested Design Values (in inches)

Resistor width	0.030 (min)
Conductor width	0.020 (min)
Spacing between lines	0.015 (min)
Metallized through hole	Diameter substrate thickness (min)
Tolerance	
Resistor width	±0.005 (easily obtained) ±0.001 (desired)
Resistor length	±0.020
Conductor width	±0.005

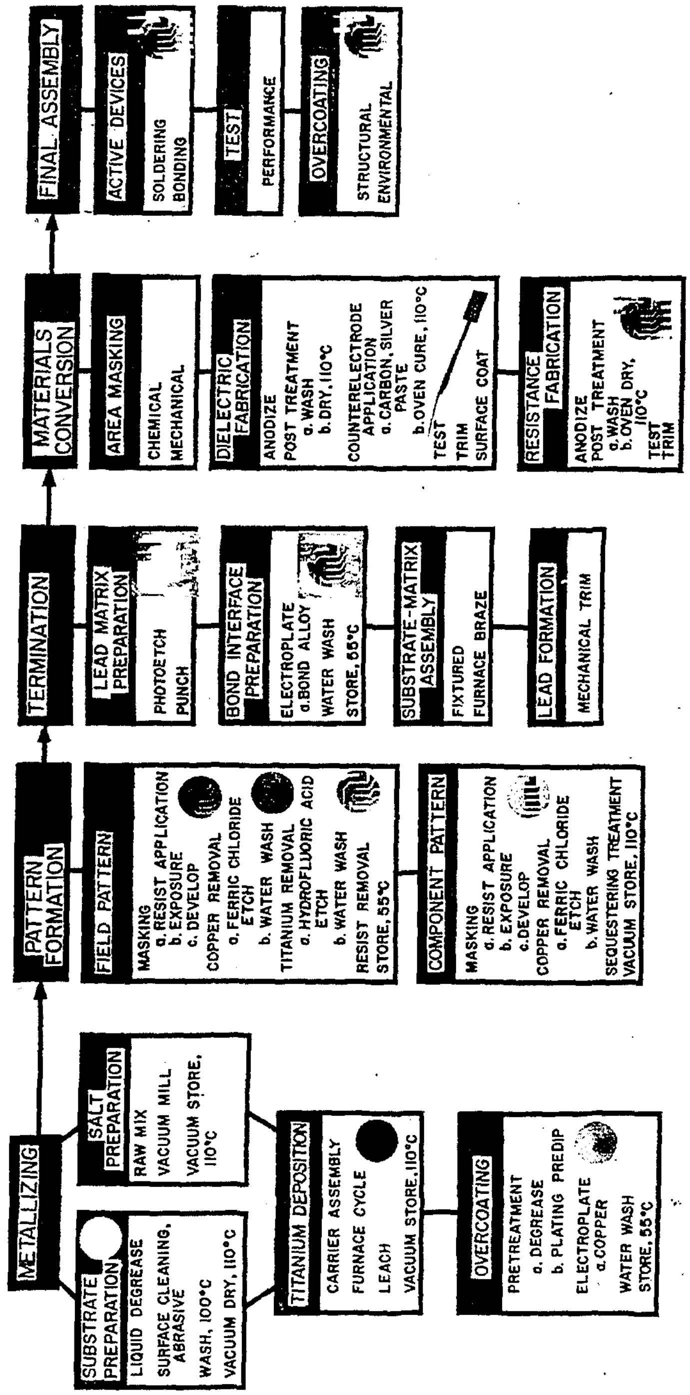

Fig. 9. Thin-film technology flow chart.

processes were investigated; the most promising of these was vacuum diffusion. This technique, which consists of heating the part to diffusion temperature in high vacuum, has proved completely successful and now produces very high yields (better than 95% acceptance).

Pattern sophistication created new problems. Films which could be anodized while making 0.250-in.-wide resistors were difficult to anodize properly on the narrower (0.030-in. wide) lines. It was discovered that the films could be made even thinner and still maintain proper uniformity. Therefore, the metallizing technique was refined to produce thinner, more uniform films. These new films produced variations in the conversion process, and these variations, in turn, required alterations in techniques, processes, and equipment in order to produce usable parts.

Requirements for anodizing impose some restrictions on the circuit layout. Resistors of the same ohms-per-square value are anodized in a second setup. A 0.030-in.-wide clearance around the resistor group is required for the gasket of the anodizing cell or anodizing mask. The conductive paths which connect to resistor groups should be located on opposite sides of the resistor group. The other two sides should be free of connections. The copper overlay on the conductors should extend no closer than 0.030-in. from the edges of the anodized area. (If the copper comes into contact with the anodizing fluid, voids due to arc-over and sputtering result.)

This type of chain reaction, where a slight change somewhere in the process affects many other operations within the process, is typical of many research problems. Indeed, this is one of the basic processing problems where each processing operation is dependent on all other operations.

ELECTRONIC CIRCUITRY HEADACHES

As the result of continued development, the MSE thin-film processes became well-controlled when a new set of problems arose; these were electronic circuitry headaches. Circuit designers found that they had to work under a new set of design restrictions. One of these restrictions limited the size of the largest single resistor which could be used. This restriction was based on several factors: optimum ohms-per-square which could be produced, space available on standard substrates, width of line capable of being produced in the photoetch process, and characteristics of the conversion process. Capacitor design is similarly limited, largely for the same reason. The number of resistors per substrate is limited by the size of the substrate, by the spacing necessary to preserve electrical integrity, and by the acceptance rate of the process. Of these, the acceptance rate of the process is important since statistically the reject rate is directly proportional to the number of "components" per substrate.

Equipment Headaches

Equipment such as electron beam welders or thermal compression bonding devices, which could eliminate some of the assembly problems, is too expensive for a laboratory setup and is incompatible with economical chemical processes. Other alternatives, such as furnace-brazing of leads, are now being developed.

Much of the commercially available equipment is unsuitable for processing conditions. The equipment may be too large (such as printers and etchers developed for printed circuit boards) or too small (such as micropositioners and similar equipments developed for the semiconductor industry). Other equipment is simply not adaptable to these techniques.

The unavailability, excessive expense, and unwieldiness of commercially available equipment has led to our own development of much of the processing equipment. This equipment, which must be kept simple and inexpensive, is designed to be as trouble-free as possible. Consequently, very little down-time occurs on the pilot line.

MORPHOLOGY HEADACHES

The first product of the pilot line was a NAND circuit, composed of five resistor elements and one transistor, for evaluation by one of LMSC's Research Computer groups (see Fig. 10). This circuit has been produced by conventional miniaturizing methods; the smallest assembly was 0.6 in. square. Therefore, in order to produce a replaceable unit, no choice was available for configuration change. This always presents a problem. Placement of leads, resistors, and the transistor was not optimum for thin-film application. A much smaller transistor could have been substituted with minor circuit redesign. The resistance values could have been reduced and the $\pm 1\%$ resistance tolerance could have been relaxed with redesign. Nevertheless, good parts were produced, even though they were much larger than required. The result was an unfortunately high reject rate and a long fabrication time.

The first NAND circuit design led to many improved design techniques.

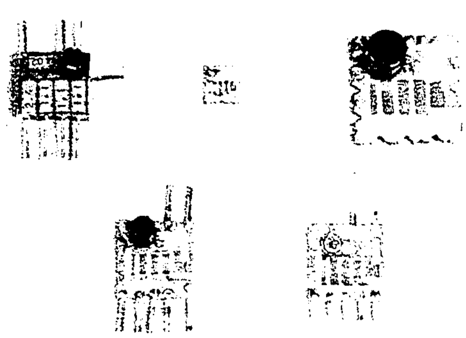

Fig. 10. NAND circuit.

From a processing standpoint, it was found more advantageous to place as many resistors as possible in one area rather than scatter them throughout the substrate. Resistors which could not be forced into this arrangement were placed in the most convenient area which the designer could devise. Also, the resistors and capacitors must be kept at a distance of 0.030 in. (minimum) from the edge of the substrate to avoid the edge effects and slight irregularities which can easily occur on substrate perimeters.

Leads should not be permitted to exit from the substrate at random. It is desirable to attach leads to one edge only; however, this goal is rarely obtainable, since it is more usual to have leads on two sides rather than one. There are some designs, however, in which leads exiting from three sides are inescapable.

It became obvious as other circuit designs were attempted that additional considerations were necessary. Design problems of a low-power flip-flop circuit (Figs. 11 and 12) indicated the necessity of placing all resistors on one side of the substrate and all capacitors and active elements on the other. This was dictated by certain processing and assembly conditions.

The next thin-film integrated circuit project was to fabricate a 10-stage scaler

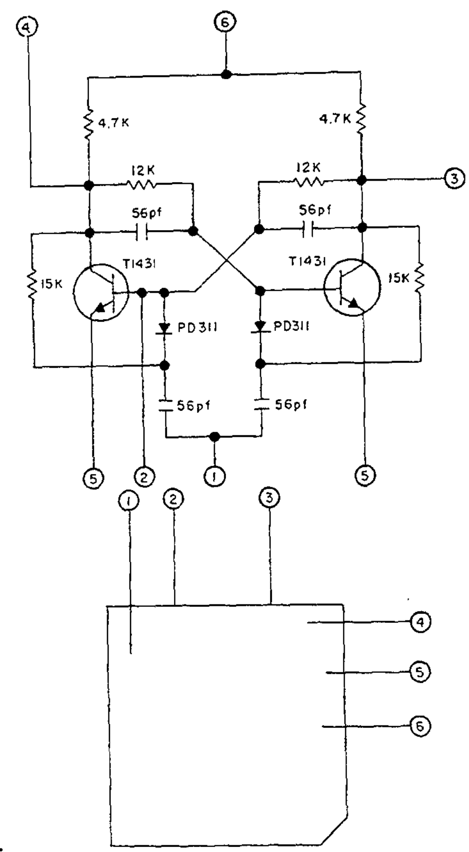

Fig. 11. Low-power flip-flop schematic.

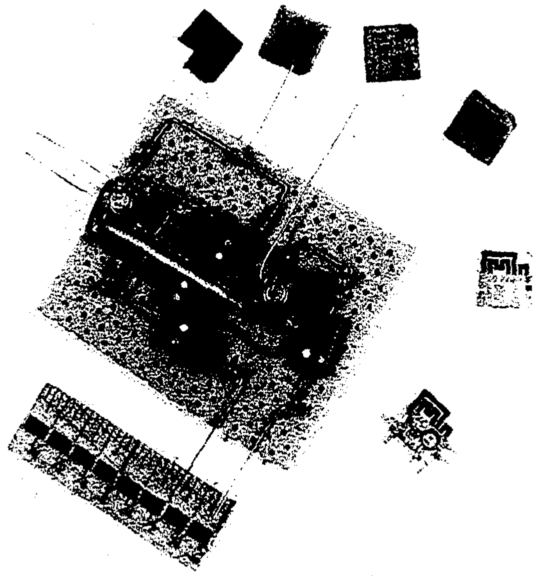

Fig. 12. Low-power flip-flop-breadboard and processing steps of thin-film integrated circuit.

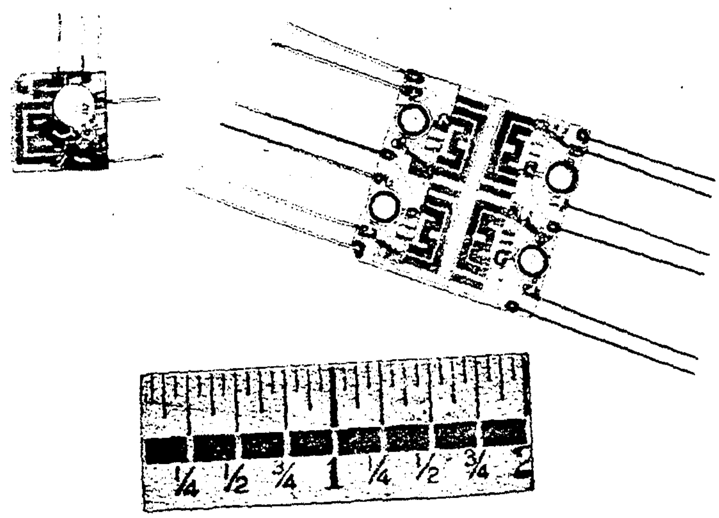

Fig. 13. Thin-film integrated flip-flop and four-stage flip-flop.

consisting of four 1-in. substrates, each of which carried four complete flip-flop circuits (Fig. 13). Each substrate contained 28 resistors, 16 capacitors, 8 transistors, 8 diodes, and 22 exit leads.

The assembled scaler had 24 exit leads (Fig. 14). This project taught us many valuable lessons. We learned the importance of an intersubstrate connection system or scheme. Previous studies and experiments had been concerned primarily with single wafers which would not be interconnected. Unfortunately, the full significance of this problem did not become apparent until the scaler was ready for assembly.

The design was based upon individual units; therefore, the interconnection scheme was not optimum and was sufficiently awkward to preclude a systematic assembly. Both the NAND circuit and the 10-stage scaler presented examples of the kinds of problems encountered on the pilot line because the designer failed to take advantage of the existing technology. The NAND circuit has since been redesigned and has been produced as a much smaller assembly with high fabrication yield and excellent reliability features. The 10-stage scaler will be redesigned and produced in the future as this technology progresses, and will help establish a firm relationship between fabrication yield, number of functions or elements per substrate, interconnect methods, substrate size, and reliability. Thin-film integrated circuits are now being designed as complete packages using the "mother-board" interconnect technique rather than being designed as separate circuitry functions which are unsystematically joined together.

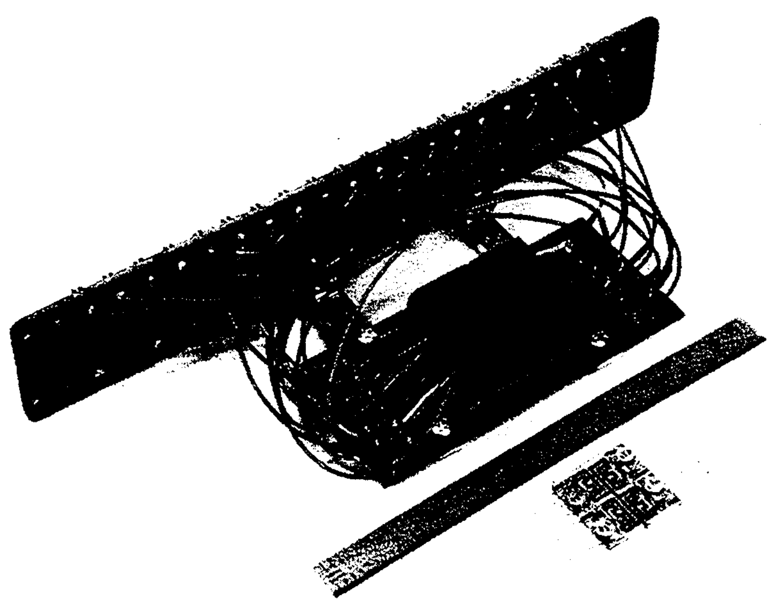

Fig. 14. Ten-stage scaler—multiple exiting leads.

Another valuable lesson learned was that it is impossible to "fight the percentages." The 28 resistors on a single substrate necessitated an acceptance rate of better than 96.5% in order to produce any usable parts. At this early stage of the process development, this high percentage was difficult to achieve. An extremely high reject rate had to be overcome before the required number of substrates were produced. Since this time, substrates have been designed with fewer resistors. Consistent processing improvements have also improved the acceptance rate. In addition, "spare" resistors have been designed into some units which provide alternates for occasional out-of-tolerance resistors.

This project also taught us much about the assembly of the substrate, that is, the methods of attachment of active elements and exit leads. While present methods are sufficient, research continues in the development of methods which will improve the product. As the active elements which electronic designers desire to use become smaller and more delicate and the interconnects become more elaborate, these assembly problems are certain to become more acute. For instance, it has recently been noted that 0.001-in. gold leads on certain transistors tend to alloy with solder rather than to make a joint; this requires special handling in order to make connections.

CONCLUSIONS

An attempt has been made to point out some of the problems in operating the MSE pilot line. Problems fall into several broad classifications: circuit compatibility, and morphology, technique or technology, and equipment. None of these problems is insurmountable, but all are annoying. With each problem, some new and useful bit of technology or information is derived. Indeed, even those problems which remain unsolved yield some useful increment to technology.

Operation of the MSE pilot line emphasizes the requirements for integration of design, materials, and processes. Much progress has been made since the first crude attempts at producing thin-film components and assemblies. Overall technology of films and knowledge of metalizing are superior to those that existed prior to the pilot line. The pattern formation, pattern resolution, and conversion processes are also much improved. A reduction has been made in the reject rate, and the acceptance rate greatly increased. Yield, aging, design, and performance data have been accumulated for reliability purposes. The end joint in size reduction will largely be governed by the ability of the photoetch and conversion processes to achieve the necessary fineness of technique.

As to the future, we expect that the number of headaches will be inversely proportional to process improvements. We expect larger headaches from smaller part sizes. We might ask whether it is possible that as the thin-film circuit approaches smaller and smaller sizes, the associated troubles will turn into one immense, infinite headache—a megaheadache?

ACKNOWLEDGMENT

The discussion in this paper is the result of a series of programs which has been supported by LMSC Independent Development Funds. Credit for the success of these programs belongs to the entire staff of the Microsystems Electronics Department. The authors wish to acknowledge the diligent and dedicated efforts, which have carried the programs closer to the goal of developing processes, materials and design information to achieve a producible, more reliable, thin-film integrated circuit technology.

DISCUSSION

Q. (C. Murn, Grumman Aircraft, N.Y.) You mentioned brazing of the tab to the thin film. Would you elaborate on that please?

A. One of the processes in fabricating a titanium thin-film circuit is to electroplate a conductive coating such as copper over the entire thin-film deposited substrate. This copper coating has several functions, two of which are to serve as a conductor and as an etchant resist during the pattern formation process. Adherence of the electroplated material to the titanium film is rather poor, consequently, an additional process, diffusing the copper into the titanium film, must take place after the pattern has been formed. It is during this thermal diffusion process that leads are brazed to the conductor tab areas on the substrate. These leads, being securely attached to the circuit with a high-melting material, can later be soldered or welded without the possibility of becoming detached due to high temperature.

Q. (Al Acken, RCA, Van Nuys, Calif.) Do you depend upon the reduction of the thickness of the film, or the change into the oxides of titanium as the control of the ohms per square?

A. Resistance of the film, measured in ohms per square is essentially changed and controlled by reducing the thickness of the film. Titanium is initially deposited on the substrate to approximately 10 ohms per square and reduced in thickness in selected areas to approximately 1000 ohms per square. Reduction of the film thickness is accomplished by converting the surface area of the film into oxides of titanium

Q. (G. Mouri, Jet Propulsion Lab., Pasadena, Calif.) What is the composition of the metallizing salt used in your process? What are the characteristics of the electroplating operation?

A. Composition of the metallizing salt is Lockheed proprietary data, however, a portion of it is sodium chloride. Copper electroplating is done in the normal cyanide bath strike followed by further acid copper-plating.

Q. (R. Malarik, Lear Siegler, Grand Rapids, Mich.) What sort of electrical tolerance do you achieve on resistors you make in this manner?

A. We have processed resistors to a tolerance of $\pm 1\%$.

Q. (Al Gaetjens, General Electric, Valley Forge, Pa.) How much deviation do you have between resistors on one single piece; in other words, will they fall within 1% when converted as a group?

A. With laboratory control of the various processes we have had groups of resistors formed which are all within $\pm 10\%$. If a closer electrical tolerance is required, those few resistors which are outside the tolerance range are individually adjusted by further anodizing.

Q. (J. Wicks, Centralab, Milwaukee, Wis.) I understand you use a high-alumina-based material for your substrate. If so, are you lapping or grinding them before you deposit the film?

A. We are presently using an "as received" alumina substrate produced by American Lava Corporation which is 96% pure. Impurities are MgO and SiO_2. It is not necessary to grind or lap the surfaces.

Q. What minimum line widths have you been able to maintain on your conductors?

A. As a general design rule we presently are using 10-mil lines as the minimum conductor width. We expect to reduce this to 5-mil width in the future.

Conductive adhesives

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Microelectronic Connections

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This paper presents a discussion of microelectric connections and microminiature electronic design. Included are a section on circuit design philosophy, descriptions of conductive adhesives currently in use, and a discussion of the gold foil and gallium alloy connection techniques.

INTRODUCTION

A CONSIDERABLE challenge in microminiature electronic design is presented by the problems of making satisfactory electrical connections.

As the size of electronic parts tends to become progressively smaller, the amount of wiring in sophisticated electronic equipment becomes proportionately greater. Probability of connection failures and bulk of interconnecting wiring place practical ceilings on microminiature equipment design.

A critical design approach to microminiature module interconnection shows that the number of interconnections increases at a rate greater than the number of modules being connected. Use of larger-size modules, preferably in a flat configuration, can minimize this connection problem. A book type of assembly, utilizing these flat modules, can provide the required access to all parts for repair and servicing.

The extremely small size of electronic parts and lead wires complicates the connection problem. Since conventional methods for making electrical connections are difficult or impractical in many instances, an evaluation of new techniques is necessary. Conductive adhesives, which are adaptable to the flat module approach particularly for use with dot geometry parts, have been evaluated and found generally satisfactory for use in space equipment environment. Effort has also been expended on two other low-temperature techniques for making electrical connections. These are the tamped pure gold foil technique and the gallium alloy technique, both of which show promise of solving some of the connection problems of microminiature equipment.

CONNECTION DESIGN PHILOSOPHY

Fostered by an unremitting demand for more sophistication and greater performance, the complexity of electronic equipment tends to increase without limit.

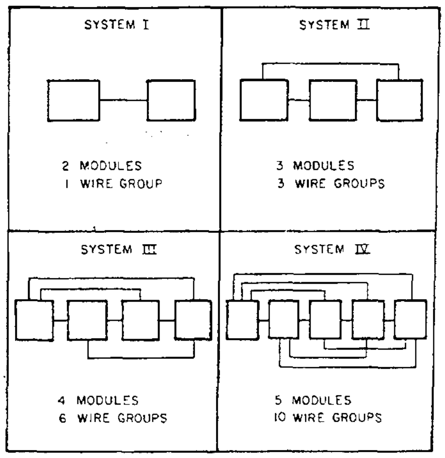

Fig. 1. Interconnection complexity as a function of number of modules.

To keep the volume of this equipment within reason it has been necessary during the past fifteen years to miniaturize, subminiaturize, and microminiaturize. It is apparent that these efforts must continue, and indeed be intensified, if we are not to be ultimately engulfed by the sheer bulk of our electronic servants.

Excluding some advanced solid state techniques from immediate consideration, a generally satisfactory approach to the problem of keeping equipment from becoming too large is to reduce the size of the parts. However, this method now brings us to a paradoxical situation in which the volume of electronic parts is under control, but the amount of wiring continues to increase.

The basis for this increase in the amount of interconnecting wiring is very simple (Fig. 1). If two modules are interconnected, only one group of wires is

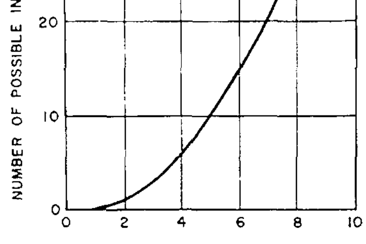

Fig. 2. Tendency of interconnections to increase as the square of the number of modules.

required. But three wire groups are needed to connect three modules, six wire groups for four modules, ten wire groups for five modules, and so on. If the simplifying assumption is made that some mean number of wires may be assigned to each wire group, then it is apparent that the number of interconnecting wires tends to increase in proportion to the square of the number of modules (Figs. 2 and 3).

It can be seen (Fig. 4) that if two electronic parts are connected together on the same substrate (Type A), using conventional printed circuit dip-soldering techniques, the number of connection junctions is four. If the two parts are on separate substrates (Type B) or in separate modules, the number of junctions is ten. These numbers may be reduced by employing other techniques, such as welding, but Type B will always have more junctions than Type A by an appreciable factor regardless of the technique used. Thus it is apparent that good design practice, insofar as connections are concerned, should tend toward Type A. Poor designs tend toward Type B.

Carried to the logical extreme, Type A construction would result in each complete assembly or system being a single module with a minimum number of

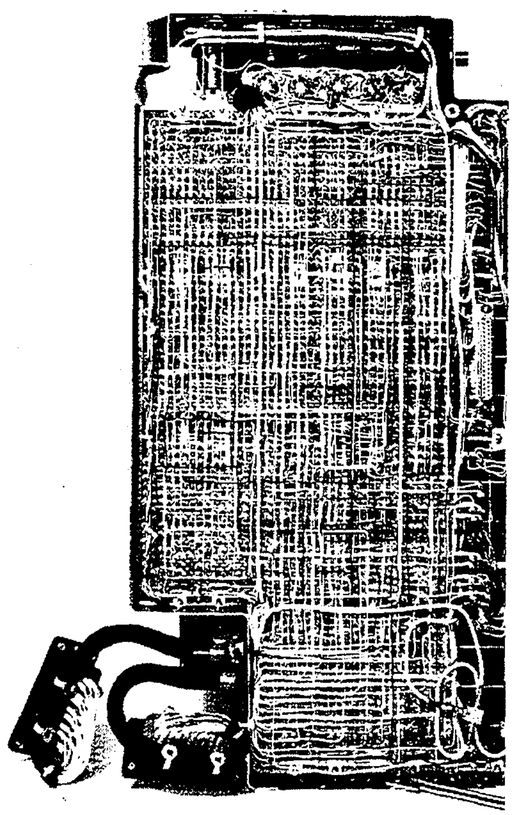

Fig. 3. Assembly occupying less than 1 ft^3 of volume containing more than 18,000 connections.

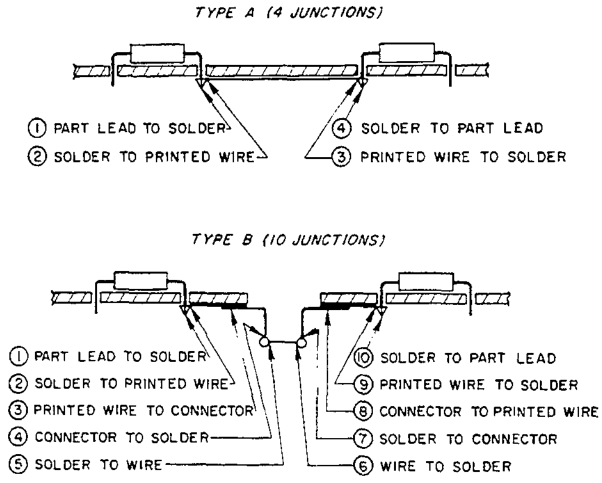

Fig. 4. Design for minimum number of electrical connections (Type A) compared with poor design practice (Type B).

connections. Type B construction on the other hand, carried to its logical extreme, would result in the maximum number of the smallest possible modules with a maximum number of connections.

The logical course of action is to select a construction which approaches Type A as closely as possible commensurate with other factors such as unit dimensions, repairability, environment, and similar items.

In addition to the considerations of volume and weight, wiring is normally a major contributor to equipment failure. Thus, unless something is done to alleviate the situation, the wiring ultimately places a ceiling on the degree of complexity to which it is practical to build a system.

In solving the connection problem, generally the most effective effort is the reducing of the number of connections per component to the lowest practical number. This reduction can be realized by increasing module size.

The justification for improving reliability by increasing module size is very easily demonstrated. If the independence of failure probabilities is assumed, the probability that a system will have no connection failures in a given time interval may be expressed as follows:

$$P_s = P^N$$

where P is the probability that any connection is satisfactory for a given time interval, P_s is the probability that the system will have no connection failures in a given time interval, and N is the number of connections in a system.

It is obvious that any decrease in N will have a significant effect on P_s since P is always less than one. P_s may also be increased by causing P to approach unity. However, this is a process problem since P approaches unity only as our process skill approaches absolute perfection. N, on the other hand, is independent of processes. For a system comprised of a given number of components, N is a function of the manner in which the system is subdivided into modules.

On the above basis it is possible to deduce the proper size and shape of a module, in a general way, reasoning as follows:

1. Because of the $P_s = P^N$ relationship, it is essential to reduce N.
2. N can be reduced by increasing module size.
3. Practical fabrication, handling, and installation considerations limit module size; 6 or 8 in. would seem to be a practical maximum for any module dimension.
4. Modules with a thickness of more than one or two electronic parts are difficult to fabricate and cool if the other dimensions are large. Therefore one dimension of the module should be small with the value of this dimension dictated by the electronic part and substrate thicknesses.

Thus the geometry of the ideal module appears to be reasonably flat (Fig. 5) with a thickness of a fraction of an inch and a length and width of several inches each. This geometry should hold regardless of the fabrication technique. Using advanced microminiature parts or thin-film techniques, between 100 and 1000 component parts should be possible in modules of this size. This is roughly an order of magnitude greater than the number of parts in currently accepted configurations or popular versions of module design.

This module geometry is idealized from the standpoint of reduction of connections. Another beneficial result is the ease of heat removal accruing to the geometry. However, from other points of view the geometry may be a disadvantage. For example, for thin-film construction, the yield problem introduced by the necessity of so many components on a single substrate becomes severe (Fig. 6). If a module yield of 50% is to be attained the yield on the individual electronic component parts must be approximately 92% if a module contains 10 parts, and in excess of 99% if a module contains 100 parts.

On the other hand, dramatic results can be obtained with this geometry: in one instance, a 300-component-part subunit comprised of 17 modules contained more than 1000 connections of which, approximately 200 were of the plug-in or disconnectable type. In redesigning the subunit into a single 300-component-part module, the connections were reduced to slightly more than 600 with only 11 of these disconnectable. This represents a decrease in the total number of connections by a factor of approximately two. Disconnectable connections were decreased by

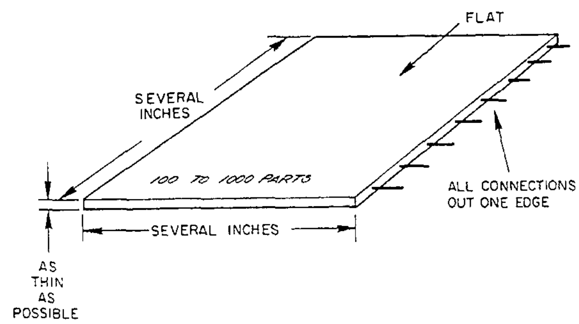

Fig. 5. Idealized module geometry from standpoint of decreasing the number of connections.

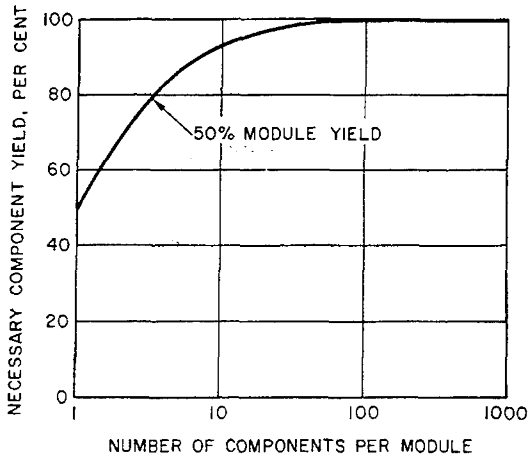

Fig. 6. Fifty percent module yield curve for increasing number of components per module.

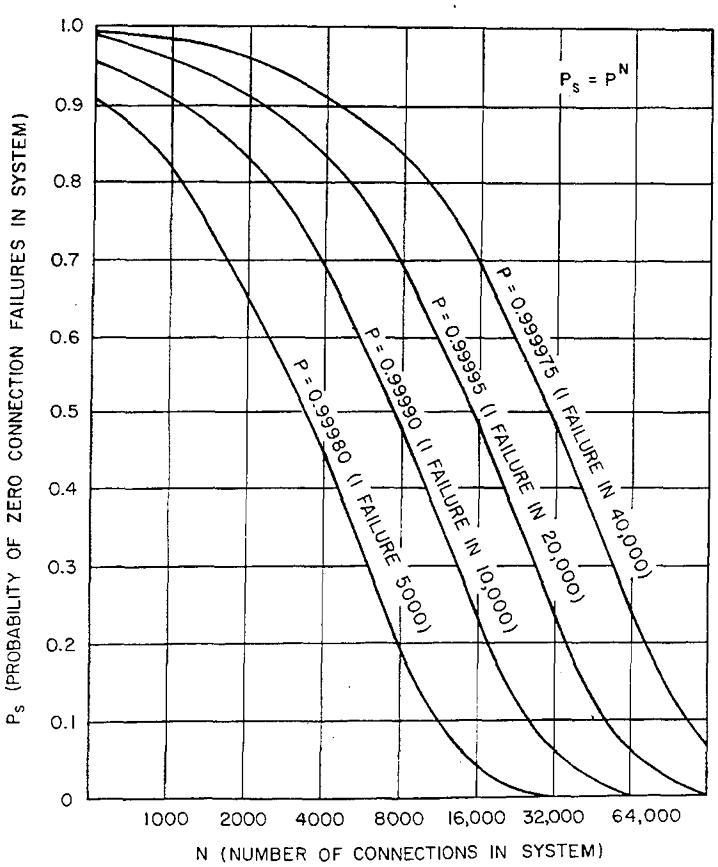

Fig. 7. Probability of zero connection failures as a function of number of connections for various failure rates.

a factor of approximately 20. Such decreases can lead to significant improvements in reliability.

For a complete electronic system, the magnitude of the improvement in reliability can be shown by plotting a set of connection failure rate curves against P_s and N (Fig. 7). These curves are quite steep in the central section where the greatest gains in system reliability can be achieved by reducing the number of connections. Systems with relatively few connections (which lie to the extreme left) profit only slightly by connections reduction. Systems with very large numbers of connections (which lie to the extreme right) are probably impractical.

Having eliminated as many connections as possible, it is still necessary to make those connections which remain—both *interconnections* (the connections between modules) and *intraconnections* (the connections within the module).

Interconnections are traditionally disconnectable connections to permit modules to be removed for maintenance. Although many good connectors of this type are on the market, it is generally conceded that a disconnectable connection is less trustworthy than a permanent welded or soldered connection. The disconnectable connector is designed to disconnect as well as connect; consequently, the ability to disconnect is inherent in its nature. That it may elect to disconnect on some inappropriate occasion is cause for no surprise. These connectors are sometimes referred to as connectable disconnectors.

If it is wise to minimize connections in general, it is doubly wise to minimize the disconnectable type. In many instances it is possible to eliminate them altogether.

One interconnection method which is adaptable to the module geometry described is the book type of assembly (Figs. 8 and 9) in which all of the interwiring is permanently connected to one side of a stack of modules. Wiring is flexible so that the assembly can be opened like a book, giving access to all parts. This type of design is particularly adaptable to modules using dot electronic parts with conductive adhesive for intraconnections (Fig. 9).

Intraconnections within modules normally constitute the major proportion of the connections in a system. For this reason, extremely low failure rates are essential. The difficulties encountered with the conventional lead–tin solder method for making electrical connections are well known to all experimenters

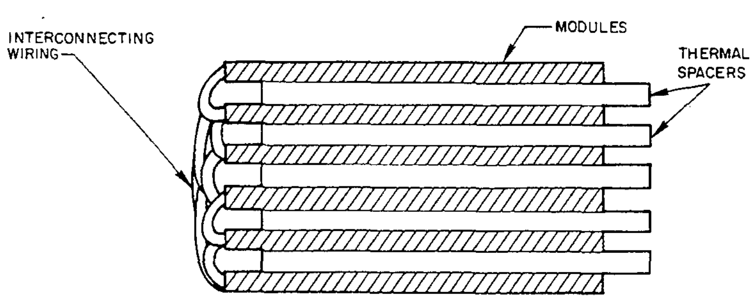

Fig. 8. Book type of assembly (end view) designed for minimum number of connections and flexible interconnections.

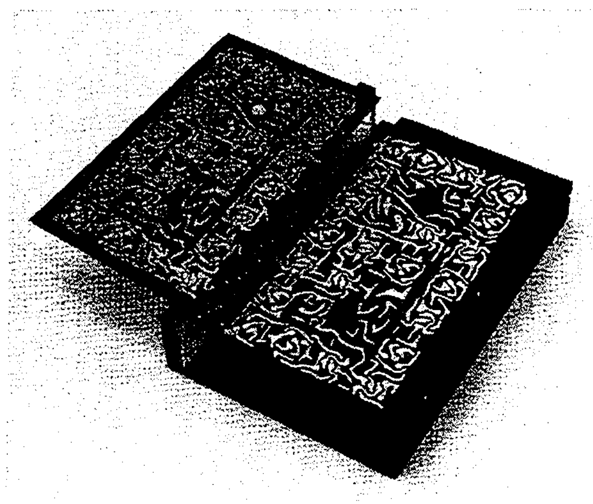

Fig. 9. Assembly using dot electronic parts and book type of interconnection design.

concerned with microminiature circuits. These difficulties include the problem of embrittlement of the wire materials, damage to parts, excessively large tools, use of fluxes, cleaning, and inspection. As a result, considerable effort has been expended in an effort to evaluate other techniques for electrical connections. Resistance welding, which is now in general use, solves some problems.

Recently, effort has been devoted to low-temperature techniques for intraconnection. One technique involves the use of conductive adhesives for making connections to dot electronic parts which have no wire leads. Two other techniques for connecting conventional microminiature parts which have been studied are the use of tamped pure gold foil and the use of gallium alloys, both of which are presently adaptable for limited application.

CONDUCTIVE ADHESIVES FOR INTRACONNECTION

Because conductive adhesives offer unique advantages for intraconnection of dot electronic parts, an investigation and evaluation of these techniques has been made. The concept involves the placement of dot parts in a flat thin wafer matrix in a predetermined arrangement. The intraconnection pattern is designed and a photographic pattern is made. The conductive adhesive is then silk-screened onto the wafer matrix, achieving connection.

The potential advantages are:

1. *A large number of connections can be made in one operation.* The only limitation is the size of a silk screen that can be reasonably prepared and handled.

2. *Connection by conductive adhesives is a relatively "cold" process.* Commercially available conductive adhesives can be cured at temperatures from room ambient to about 250°F. Dot electronic parts are capable of withstanding temperatures of at least 250°F without damage.

3. *The silk-screen process is capable of automation.* With sufficient volume demand, the mechanics of an automatic or semiautomatic process appear to be capable of resolution.

There are more than two dozen suppliers of conductive adhesive and conductive coating materials. The materials are used in many ways; the most notable of these are:

1. Providing conductive surfaces for plating of nonconductive materials
2. Metallizing of surfaces as for RF shielding
3. Repairing of electrical circuits
4. Providing rapid versatile printed wiring in experimental breadboard work

The materials consist of a conductive filler dispersed in a plastic or resin matrix. Typical fillers are carbon, aluminum, copper, gold, and silver. Plastic matrices used range from thermoplastics, such as cellulosics, to thermosets, such as epoxies and silicones.

The thermoplastic materials are commonly dispersed in solvents to facilitate application. The solvent can be removed at the time of use by air drying or by forced heat drying. The thermosetting materials may or may not be supplied in a diluent. Some formulations require the addition of diluents to permit reasonable use. Some thermosetting materials require the addition of catalysts or curing agents while some are one-part internally catalyzed formulations. Thermosetting formulations require cures ranging from room temperature to elevated temperatures as high as 250°F.

The basic objectives of conductive adhesives for intraconnection are, of course, to provide an electrical union between electronic parts and a mechanical union between the parts and the wafer or substrate.

Associated with the fundamental objectives are process and functional requirements. In addition to process requirements such as low-temperature cure and adaptability to silk screening, the general functional requirements of importance are:

1. Uniform predictable electrical properties
2. Relatively low volume resistivity
3. Relatively low electrical contact resistance
4. Good adhesion to a variety of wafer and electronic part materials

For this evaluation, certain additional functional requirements were considered. Since an important application of microelectronics is in spacecraft where size and weight are tremendously significant, two conditions of the space environment were included in the testing program. These were effects of vacuum in the 10^{-7} mm Hg range and thermal cycling, such as encountered if an orbit carries a spacecraft through rapid changes from hot to cold while moving in and out of the earth's shadow.

Selection of Conductive Adhesives

With these requirements in mind, specimen formulations were selected from the wide variety of those available which appeared to offer the greatest promise.

Silver was selected as the filler of primary interest based upon the relatively high conductivity of silver coupled with the desirable feature that common silver salts are conductive. However, gold-filled formulations have also been studied.

Epoxy-resin-based formulations were regarded as the most promising, although some thermoplastic-based materials were evaluated. The epoxies were chosen for their generally superior adhesive qualities, solvent resistance in the cured form, capability of cure without evolution of by-products, and heat resistance compared with thermoplastics.

Ten formulations from four suppliers were evaluated.

Preliminary Testing

All materials were subjected to preliminary testing which included:

1. Handling characteristics
2. Appearance
3. Adhesion
4. Volume resistivity

Test conductor paths were applied onto epoxy-fiberglass laminate (Fig. 10) by use of a metal stencil. The various formulations exhibited different handling characteristics. The thermoplastic materials were generally easy to apply while several of the epoxy-based materials were difficult to disperse in solvents. Appearance of the dried or cured materials was generally good. Not surprisingly, the thermoplastic-based materials generally were superior in appearance although the majority of the epoxy-based materials were not unsatisfactory.

Two of the thermoplastic materials were totally unacceptable from an adhesion standpoint. These two materials had essentially no bond to the substrate. Other thermoplastic materials and all epoxies were completely adequate in this regard.

Volume resistivity measurements were made and wide variations between materials were noted. For the materials tested, volume resistivities ranged from 90 to 11600 μohm-cm. Most materials evaluated had volume resistivities less than 1000 μohm-cm.

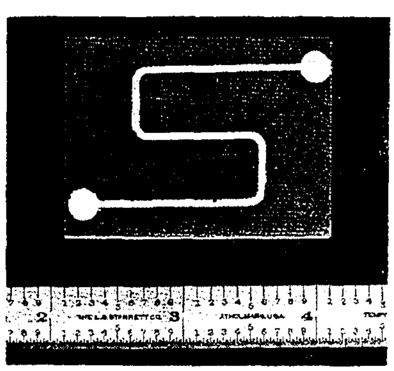

Fig. 10. Conductive adhesive straight-run test specimen.

Effects of Aging

Since the electronic units made with conductive adhesives for intraconnection would be used for long periods of time, it was necessary to know what, if any, changes in conductivity would occur with time. Specimens of all materials were divided into two groups. One group of specimens was allowed to remain at room ambient conditions and the other group was placed in an oven at 185°F. Periodic resistance measurements were made on all specimens for at least nine weeks. Behavior of different materials varied substantially. Some materials varied erratically for the entire period while others behaved more consistently. Most of the materials conditioned at 185°F exhibited a dramatic decrease in volume resistivity for about two weeks, after which they remained at a reasonably constant level.

Plots of results obtained on two materials are presented in Figs. 11 and 12. The material represented by Fig. 12 is a silver-epoxy, and was unique in its essential absence of change with aging at either room temperature or 185°F.

Resistivity-Temperature Effects

At this stage of the evaluation, one material (the epoxy-silver whose aging characteristics are shown in Fig. 12) has shown the best overall characteristics. This material was selected to receive more intensive study and all further discussion pertains to that material.

For additional design information, the effect of subnormal and elevated

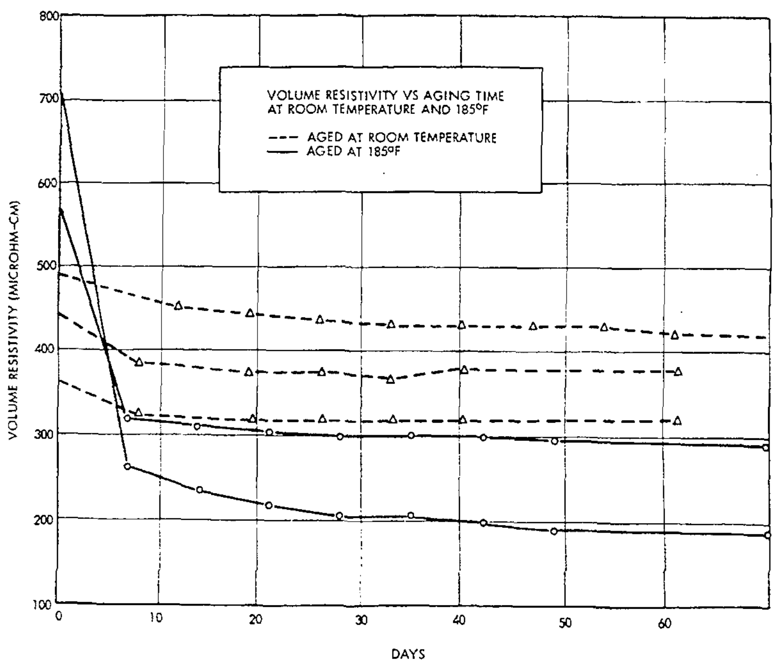

Fig. 11. Effects of aging on volume resistivity for a typical conductive adhesive.

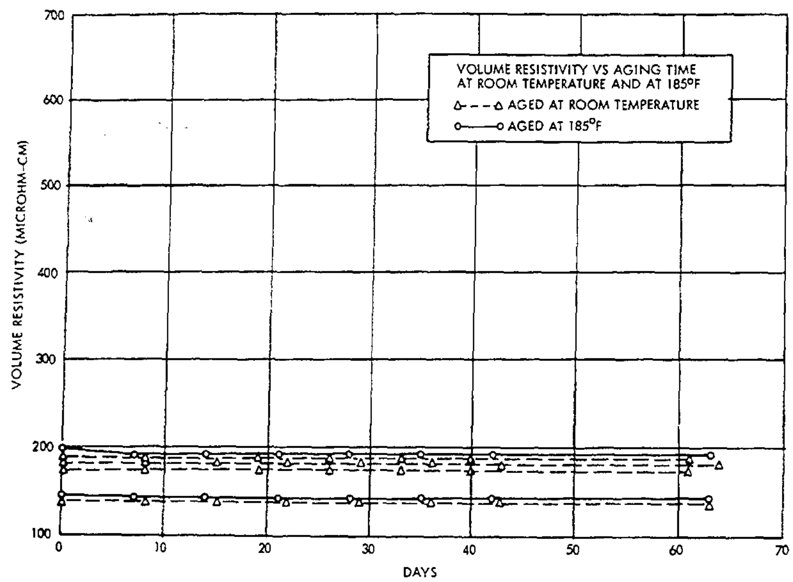

Fig. 12. Effects of aging on volume resistivity for a conductivity adhesive with excellent characteristics.

temperatures on volume resistivity were measured. Tests were conducted with the specimens at temperatures of 75°F, 135°F, 185°F and −67°F. Results are given in Table I.

The volume resistivity–temperature coefficient was calculated as

$$\frac{\Delta\rho/\rho_0}{\Delta T}$$

where $\Delta\rho$ is the difference between 75°F resistivity and test temperature resistivity, ρ_0 is the initial 75°F resistivity, and ΔT is the difference in temperature between 75°F and test temperature.

Joint Resistance and Joint-Resistance Temperature Effects

In addition to evaluating basic volume resistivity, effects of aging, and

TABLE I

Temperature, °F	Volume resistivity (μohm-cm)	Volume resistivity–temperature coefficient per °F
75°	201	—
135°	213	+0.000991
185°	223	+0.000994
−67°	158	−0.00151

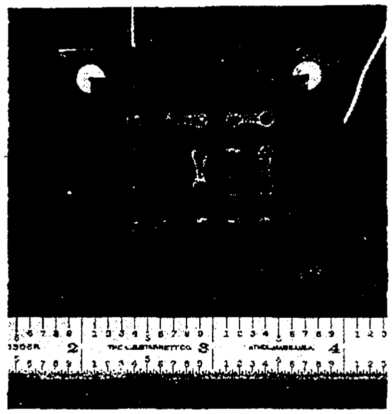

Fig. 13. Conductive adhesive test specimen for joint resistance evaluation.

temperature effects for the conductive adhesive as a printed wire, it was necessary to determine the electrical joint properties of the conductive adhesive in contact with a metallic conductor such as would occur in actual use. Specimen boards were made (Fig. 13) with gold-plated brass slugs mounted in an etched printed-wiring board and connections made with conductive adhesive. Measurements were made at 75°, 135°, 185°, and −67°F. An extended exposure at 185°F was included in the test to determine whether any significant change in joint resistance would occur with time. The data are shown in Table II.

Vacuum Exposure

The vacuum conditions of space are destructive to many polymeric materials, causing them to volatilize and sublime. Since spacecraft electronic equipment is subjected to extremely low pressures, it was desired to determine whether the conductive adhesive would be degraded by any changes in the plastic matrix.

For environmental stress tests, silk-screened specimens (Fig. 14) were used

TABLE II

Temperature	Joint resistance (ohms/component)	Joint resistance–temperature coefficient per °F
Room temperature (75°F)	0.0146	—
− 67°F	0.0110	−0.00174
+135°F	0.0166	+0.00288
+185°F at initial equilibrium	0.0183	+0.00224
+185°F after 16 hours	0.0184	—
+185°F after 22 hours	0.0183	—
+185°F after 40 hours	0.0182	—
+185°F after 46 hours	0.0182	—
+185°F after 64 hours	0.0183	—
+185°F after 70 hours	0.0182	—

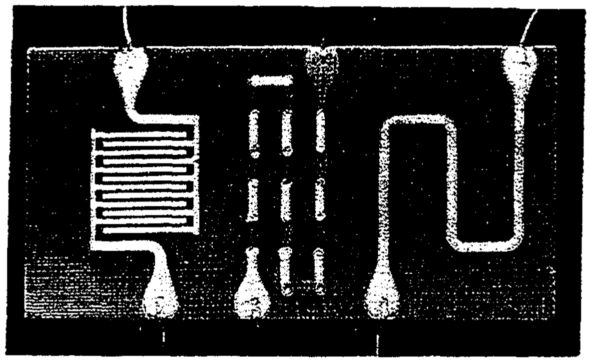

Fig. 14. Conductive adhesive test specimen for environmental stress testing.

with a three-pattern array consisting of a straight run, 19 gold-plated brass slugs connected in series, and a comb or grid pattern. Specimens were exposed in a vacuum chamber to a pressure of 2 to 3 $\times$ 10^{-7} mm Hg for periods up to 474 hr. To accelerate any destructive effects, a radiant-energy source was employed to apply heat to specimens at 180° to 190°F. Resistance measurements were made at intervals. Both volume resistivity and joint resistance decreased with time in vacuum at 185°F (Fig. 15) until approximately 325 hr, after which an essentially constant level was apparently achieved. (No breakdown or measurable decrease in insulation resistance occurred in any of the comb pattern arrays.)

Thermal Cycling

A space vehicle in earth orbit may experience rapid cyclic changes in temperature in passing into and out of the earth's shadow. Temperature extremes can be a few hundred degrees apart. The rapidity of change can produce conditions of thermal shock, a potentially destructive condition for adhesives. Varying heating

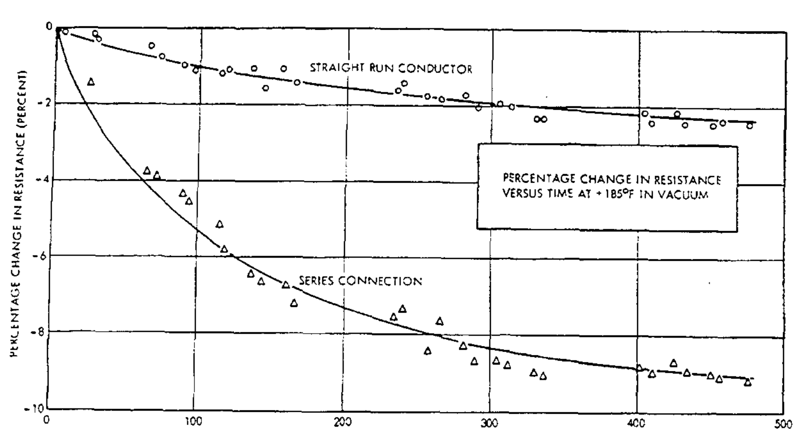

Fig. 15. Effect of vacuum exposure on resistance of conductive adhesive specimens.

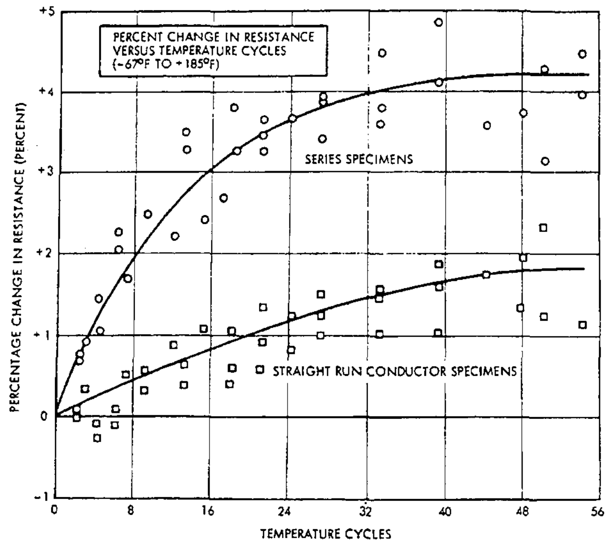

Fig. 16. Effect of thermal cycling on resistance of conductive adhesive.

and cooling rates and thermal expansion coefficients can impose stresses leading ultimately to bond failure.

Since in the application of conductive adhesives for electronic connections a bond failure can produce an open circuit, it was essential to know the effects of thermal cycling.

A thermal cycle was selected which consisted of 15 min at +185°F, 30 min to −67°F, 15 min at −67°F, and 30 min to +185°F for a total cycle of 90 min. Resistance measurements were made at intervals. A progressive increase in resistance occurred as the number of thermal cycles increased (Fig. 16). Further testing is required to determine the point at which no further increase or failure occurs. It appears, however, that the rate of resistance increase for the series-connected test pattern decreases after about 20 cycles.

A significant aspect of the testing thus far conducted is that not one instance of bond failure occurred. Four series specimens (Fig. 14) were used, each having 19 slugs connected. Since there are two sides to each slug the total number of possible bond failure sites was 152 (19 slugs, 2 sides, 4 specimens). Thus, not one of 152 possible failure sites actually failed.

High-Humidity Tests

One further environmental condition was evaluated. There are literature references to circuit breakdown and shorting occurring with silver conductors under conditions of high relative humidity. Silver is reported to undergo electrolytic migration under conditions of high humidity and applied direct current. The effect is dependent upon:

1. Relative humidity
2. Temperature

3. Voltage
4. Time
5. Insulation type, dimensions, and quality

For this evaluation, no attempt was made to determine the precise conditions for all the variables and the combinations under which silver migration would occur. Instead, three specific conditions assumed to be typical for prospective applications were selected. They were 75°F temperature, 95% relative humidity, and a dc voltage potential of 28 v applied across a comb pattern (Fig. 14). The conductor spacing in the specimen was 0.030 in. and no insulative coatings were used.

The specimen was exposed to the test conditions for periods up to 11 weeks during which time no breakdown or measurable decrease in insulation resistance was apparent.

Summary

Further testing of conductive adhesives will be required to determine conclusively the effects of factors such as thermal cycling. Testing directed toward providing data for reliability assessments will also be required.

While there are further studies to be made, the results to date indicate that conductive adhesives offer considerable promise for use in microelectronic intraconnections. Moreover, nothing in the evaluation program indicates that any insoluble problems will be encountered. It should be noted also that the materials evaluated were commercially available materials, and it is perhaps remarkable that they are as successful for the purpose as they have been. It is reasonable to assume that formulations specifically tailored for intraconnection under harsh environments could play an important role in microelectronic equipment.

GOLD FOIL AND GALLIUM ALLOY TECHNIQUES

Two types of metallic materials for making solid formed shapes at room temperature without the application of heat have been investigated for possible use in microelectronic connections. Both methods, the use of tamped pure gold foil and the use of gallium alloys, are examples of how techniques developed for one purpose may be adapted and altered for use in another field of science.

Dental scientists have experimented with gallium alloys for dental fillings similar to the familiar silver amalgam and some previous work has been directed toward their possible use in microminiature electronics. It has therefore been considered worthwhile to pursue this method further.

The tamped pure gold foil technique is also well known to dentistry but is rarely used. Its application to microelectronic connection, as far as could be determined, has not been previously reported.

Evaluation shows that both methods produce metallic bonds with mechanical tensile strength and electrical resistance characteristics comparing favorably with ordinary hot-soldering or resistance-welding methods.

Techniques for both the pure gold foil and the gallium alloy methods are developed to a point where they can now be used in microminiature electronic circuitry on a limited scale. The particular problem for which the evaluation was made was that of connecting small-gage electronic part wire leads to a substrate material. As electronic parts are progressively miniaturized, the wire leads become smaller so that many microminiature parts now have leads with the diameter of fine hair. The parts or the wires may be damaged by exposure to the heat which is inherent in hot-soldering and, to a lesser degree, in resistance-welding connection methods. It has therefore become increasingly necessary to seek new methods for making reliable electronic connections.

Tamped Pure Gold Foil Technique

Gold, owing to its high ductility, inert chemical nature, and the resultant absence of surface films, can be readily worked plastically to form a solid cold-welded mass. If wires and substrate circuit board surfaces are gold-plated, a metallurgical bond can be made between the pieces to be joined by simply tamping pure gold foil around them.

For this study, the test substrate were epoxy-glass printed circuit boards with plated-through holes. Plating in the holes was copper (0.002 in. thick) with an overplate of gold (0.0002 in. thick). The hole diameter for the test substrates was 0.070 in. (Fig. 17).

The gold used was a high-purity fully annealed foil or sheet. This material is commercially obtainable from dental supply houses wadded into what are known as pure gold cylinders in several sizes, typically $\frac{1}{8}$ in. in diameter and $\frac{3}{16}$ in. long, weighing approximately 5 mg. Cost of these cylinders purchased commercially is approximately 1¢ each.

The technique for making a tamped gold connection is as follows:

The wire is inserted through the plated-through hole in the circuit board which is clamped to a back-up plate or anvil. The backup plate is a sheet of epoxy-glass with a small drilled hole through which the excess length of the wire is threaded. Four of the gold cylinders are loosely packed around the wire in the plated-through hole using tweezers and a metal hand pick. Using an automatic dental hand mallet and plugger (Fig. 18), the gold is tamped in place until it becomes hard to the touch of the plugger and assumes a bright shiny appearance.

The mallet and plugger are commercially-available dental hand instruments. The tip of the plugger is a punch with a diameter of approximately 0.02 in. which

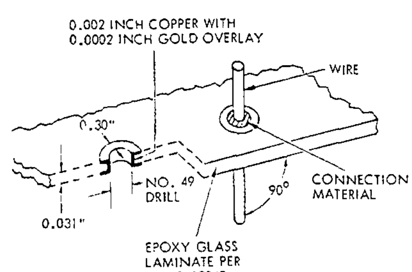

Fig. 17. Test substrate with plated-through holes for gallium alloy and pure gold foil evaluation.

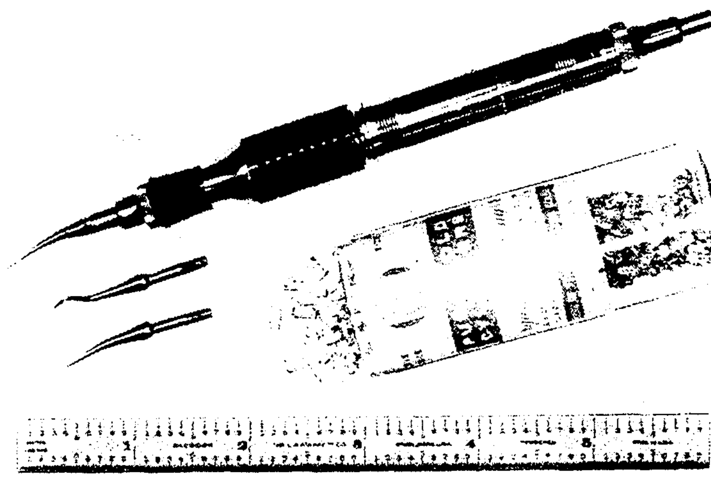

Fig. 18. Automatic dental hand mallet and plugger for making gallium alloy and pure gold foil connections.

is set into the mallet. The mallet itself is simply a handle with a trip hammer arrangement which slips under a hand pressure of approximately 2 lb. This results in a tamping pressure of approximately 6300 psi over the affected area. Other dental-type tamping tools are available operating on compressed air or mechanical power.

Hand-tamping of a gold electrical connection, as described, requires 2 to 3 min.

A photomicrograph of a typical tamped gold electrical connection cross section (Fig. 19) shows that a solid metallic bond is formed.

Gallium Alloy Technique

The metallic element gallium has interesting physical properties. With a melting point of 29.78°C (85.60°F) and a boiling point of 1983°C (3601°F), gallium has one of the widest liquid ranges of the metals. Vapor pressure is low, even at high temperatures; a pressure of 1 mm Hg is attained at 1315°C (2399°F). The low yield of the ore and lack of demand for the metal make gallium moderately expensive at prices ranging from $1.65 to $5.00 per gram.

Gallium, like mercury, combines with many metals to form amalgam-type alloys. Practical use can be made of alloys of gallium with powdered face-centered-cubic metals such as gold, silver, nickel, copper, and some intermetallic compounds of copper and tin. These alloys are soft and pliable when mixed at room temperature and harden within 2 to 24 hr. When hard, these alloys have useful temperatures of approximately 200°C.

Initially in the process, the metal powders and gallium are mixed to form a plastic mass suitable for packing into the circuit board interconnection hole. The mixing causes the gallium to wet the surface of the powders and sufficient gallium

Fig. 19. Photomicrograph of tamped pure gold foil connection to plated-through circuit board hole (gold plate on copper plate). Magnification 500 ×. Etchant: ammonium persulfate and water.

is required to wet all metal particles completely. Mixing time varies with the compound composition and method of mixing.

Gallium is quite soluble in the metal powders and diffuses into the particles as soon as they become wet. Although research has been conducted to determine the exact composition and properties of the compounds resulting from the diffusion process, the identity of the compounds formed is not well established. The reaction between the gallium and the powdered metal is primarily a surface reaction and most likely never goes to completion since the mass while still plastic is packed with sufficient force to express some of the free, or uncombined, gallium. The gallium bonds the metal particles to each other and retains the alloy in the desired compacted form. Although the initial wetting and diffusion is relatively rapid, the final stages of the gallium diffusion may continue for several hours or even a period of days.

Mixing is accomplished either by hand using a small mortar and pestle or with the use of a mechanical mixer. The mortar and pestle should be made of nylon or teflon as the gallium wets most other materials. The mechanical mixer is a commercially available unit with a small plastic cylinder and ball. Mixing occurs as the ball is agitated in the cylinder by mechanical action. Mechanical mixing is preferred to hand mixing because the mixing is controlled and automatically programmed as a function of strokes per minute and total mixing time.

Various combinations of gallium with gold, silver, copper, and nickel were prepared and tested. Tin was used as a third material in some alloys to lower the melting point of the gallium and to prolong the setting time. The tin was introduced as a gallium–tin eutectic (87% Ga, 13% Sn) or by addition of tin to the other metal powders. Gallium–tin eutectic has the advantage of being liquid at room temperature, thus facilitating mixing without the preheating required for pure

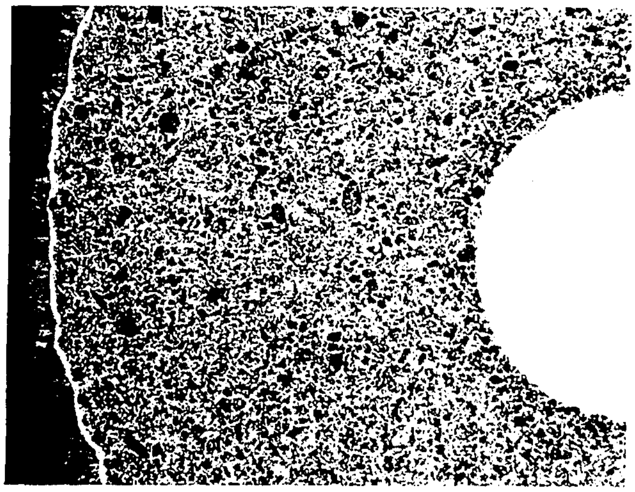

Fig. 20. Photomicrograph of gallium alloy connection to plated-through circuit board hole (35% Ga, 44% Cu, 21% Sn). Magnification 100×. Etchant: ferric chloride, hydrochloric acid, ethyl alcohol.

gallium. All powdered metals used in this study were passed through a No. 300 sieve (U. S. Standard Sieve series).

For the test program, the technique for making electrical connections was similar to that described for the gold foil technique. Wires were inserted through holes in a printed circuit board, a backup plate was placed behind the board, and the plastic gallium alloy was solidly packed around the wire using dental-type tools.

Following preliminary testing, two alloys were selected for favorable working characteristics, strength, and hardening times of 1 hr and 24 hr, respectively. These alloys were 34% gallium with 66% gold and 35% gallium with 44% copper and 21% tin.

A photomicrograph of a typical gallium alloy electrical connection cross section (Fig. 20) shows a satisfactory metal bond formed with a fairly homogeneous grain structure.

Mechanical Tensile Testing

Tensile testing of samples of connections made with tamped pure gold foil and gallium alloys was performed to determine mechanical strength of electrical connections. The test method was simple. The printed circuit substrate board was held firmly while an axial load was applied to the wire which was connected to a plated-through hole in the board. The number of pounds required to break the bond was measured using a mechanical force gage (Hunter Model D-20-T). Wire materials of various compositions, sizes, and coatings were used. For comparison purposes, the average tensile strength of the wire materials was determined and the results were also compared with the minimum acceptable strength for resistance-welded wire connections. For each gold and gallium alloy connection, a minimum of 20 samples was tested.

The results (Fig. 21) showed that in all instances the mechanical tensile

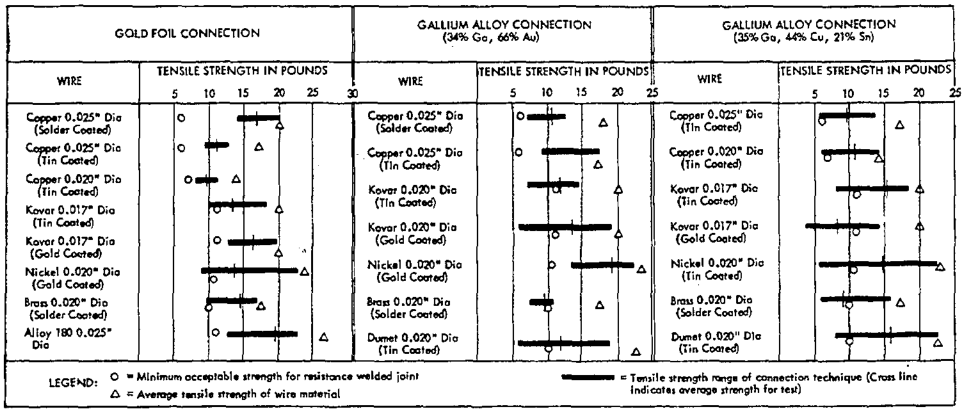

Fig. 21. Comparison of tensile test strengths of various connection methods.

strength of the gold and gallium alloy samples was satisfactory, ranging generally between the minimum acceptable strength for a welded connection and the average tensile strength of the wire. In a few instances, the strength of the gold and gallium alloy connections was below the minimum welded strength. For connection of microminiature electronic parts, however, most or all of the strength values can be considered as fully adequate for the purpose.

Electrical Resistance Testing

A standard four-terminal test method (Fig. 22) was used to determine the electrical resistance of the various connecting materials. Test samples (Fig. 23) were fabricated to allow 0.025 in. of the connecting material to be packed between the leads. For comparison purposes, data were also obtained for ordinary (63% tin, 37% lead) hot solder.

Results of the testing (Fig. 24) showed that the tamped pure gold foil connection has a lower resistivity and greater uniformity than the soldering method commonly used for electrical connections, providing improved electrical characteristics.

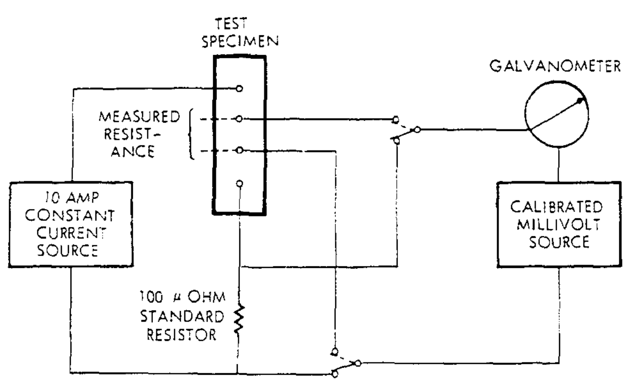

Fig. 22. Four-terminal test method setup for resistance testing.

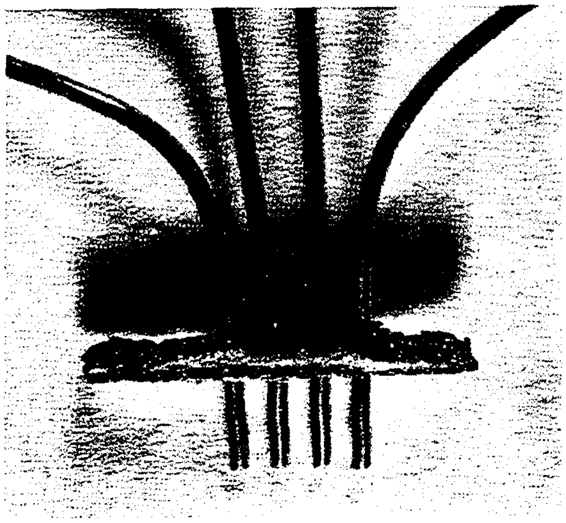

Fig. 23. Test specimen of gold foil intraconnection material for resistance testing (magnification 5 ×).

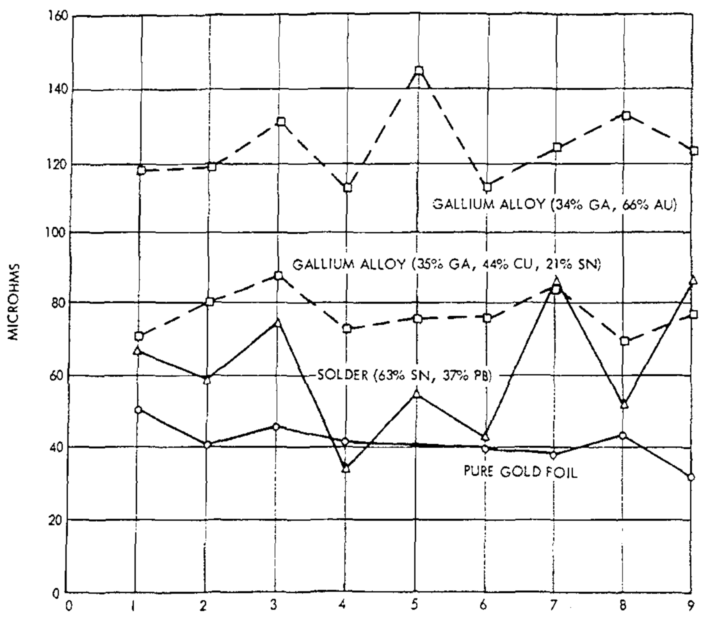

Fig. 24. Electrical resistance test measurements for gold foil, gallium alloy, and solder.

One of the gallium alloys (35% Ga, 44% Cu, 21% Sn) showed electrical resistivity generally within the same range as the solder, but with slightly better performance. The second gallium alloy (34% Ga, 66% Au) showed electrical resistance levels almost twice those for solder and a somewhat broader sample-to-sample uniformity than that obtained with either the gold foil or the other gallium alloy. The resistance for this sample, however, was within the useful range for electronic circuitry.

Conclusions

Metallurgically sound joints with acceptable strength characteristics and favorable electrical resistance were produced with both gold and gallium alloys. Results indicate, however, that gold is preferable and, in addition, is easier to store and handle with the following advantages:

1. No weighing or mixing of components involving associated process controls
2. No pot-life or shelf-life limitations exist
3. No corrosion or compatibility problems occur with pure gold because of its inert chemical nature

The extraordinary wetting properties of gallium create a handling problem. When plastic gallium alloy is applied to the intraconnection hole, care must be taken to prevent the gallium from touching surrounding areas since a thin film of the gallium will cause a low-resistance short circuit. Another handling problem is concerned with the method of mixing which may cause an exothermic reaction. Although this reaction can be controlled, the possibility is at odds with the basic purpose of this technique which is the avoidance of heat.

The time and effort required for making and compacting gold foil and gallium alloy joints are comparable. However, for a thin or brittle substrate or a relatively inaccessible joint, the use of the gallium alloy may be preferred because lower compressive forces can be used for forming the joint.

Although the automation of joint-forming techniques has not been thoroughly investigated, some consideration has been given to this matter. There are many problems to be solved before an automatic or semiautomatic connection technique can be developed for production fabrication. Additional testing also appears to be indicated to determine the useful temperature range of these two techniques, behavior under vibration, electrical potentials and similar performance characteristics. However, for limited applications involving small quantities, these processes may find definite use.

ACKNOWLEDGMENT

The authors are indebted to T. H. Cooper for his help in editing this paper.

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DISCUSSION

Q. (Dean Bailey, Motorola, Phoenix, Ariz.) Why do you bring all leads out one side?

A. This is a convenient way to interconnect stacks of modules arranged like pages in a book. Disconnectable connectors can be eliminated in this manner.

Q. (Leonard Schehr, Martin Co., Baltimore, Md.) Is silver migration a problem? If so, do you have some special way of taking care of it?

A. Silver migration is possible but can be avoided by use of good-quality insulation, by maintenance of electric field gradients at reasonable levels, and by suitable protection of the conductors from extremely high humidity.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) Are conductive cements adversely affected by thermal shock, mechanical shock, or by a combination of both?

A. Mechanical damage is unlikely since the conductors will be coated and the cards will be stacked and compressed. Thermal shock degrades the conductive adhesive connections somewhat. Additional testing is needed to determine the full extent of this effect.

Q. (Tom McCloskey, Motorola, Phoenix, Ariz.) Do you have comparative noise figures on the conductive adhesive *vs* soldered and welded joints?

A. No.

Q. (Jay Block, Aerospace Group, Hughes Aircraft, Culver City, Calif.) Relative to the tamped gold interconnection, have you tried any techniques (for application) other than the hand dental tools?

A. No. We sought only to determine the quality of connections so made.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) You have argued strongly against the use of the take-apart connector. Is this on the grounds of reliability or weight and volume? Will not continued improvements in these connectors make these problems disappear?

A. The main argument is reliability. If a connector is designed to disconnect this ability is inherent in its nature and therefore, sooner or later, it may disconnect whether you want it to or not. We have tried to show that it is possible to design equipment without using the disconnectable type. The other objection is size and weight. Connector assemblies are becoming considerably wider than the things which they are connecting. It is certainly conceivable that these problems will disappear as connector designs improve.

Point of Information (Al Rosenberg, Garde Mfg., Cumberland, R.I.) In 1961, in the Microelectronics Section published by the IRE group on military electronics, there was a paper entitled "Thermal Design Approach to High Density Computer Packaging" where thermal limitations of this kind of packaging were reviewed and analyzed and it offers very strong support for this kind of packaging from the standpoint of thermal dissipation.

Mechanical Design of Electronic Circuit Packages for Missile Environments

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Light Military Electronics Department, General Electric Company, Utica, New York

This paper is a report of an integrated design and manufacturing technique called modular weldment, developed from an attempt to find common denominators in the area of module design. Modular weldment is found to be directly applicable to aircraft, ground, and test equipment, without cost penalty, and sometimes even cost reduction.

INTRODUCTION

ANYONE WHO designs electronic circuits for missile environments is besieged with both gimmicks and advice. As each new development is reported and proved feasible, designers are urged to modify their approach to incorporate "this advance in the state of the art." But designers do not have the time to investigate the effects of such modifications on their products. Lead time is becoming shorter, and cost pressures are building up; the designer must try to find design approaches that are common to varied applications. All too often, however, a given package's requirements are unique, and only portions of previous designs or new developments can be used.

Distinct packaging techniques have been developed for such commercial equipment as radio and television, for aircraft communications and control systems for military ground equipment, and for missile and space vehicle guidance and instrumentation. Unfortunately, a more or less random interchanging of some of these applications has taken place. Sometimes because of cost, other times because of expediency or a blind desire to standardize, less than adequate methods have been used.

It cannot be overemphasized that a packaging technique for the individual stage or circuit will have serious consequences for the product design. Every ounce removed, every fastener or accessory item eliminated, every increase in vibration-response frequency will decrease the penalty in weight, volume, and cost necessary to meet the package's environmental specifications. Within the space allotted to electronic equipment on a missile, aircraft, or space vehicle, the weight and volume of the various packages determine the quantity of data and the instructions that may be transmitted and received.

Where severe environments are to be encountered, it becomes mandatory that the packaging techniques satisfy all conditions. Use of less-than-optimum methods of joint connection, support, thermal paths, RF shielding, and layout incurs an overall package penalty.

For any one application, components and connections must have a particular configuration. Because a "standard" packaging technique must be extremely flexible, a relatively simple connection method should be chosen to eliminate unnecessary variables and tolerances. In short, all material used and all operations performed must be completely functional and must become a part of the product.

Ease of manufacture is a measure of the efficiency achieved in the various design areas. A well planned and integrated design will result in a minimum of manufacturing difficulty. Electronic components of high quality will also keep replacement and rework to a minimum.

These quality components together with a repeatable, uncomplicated manufacturing process will ensure inherent component quality. Resistance-welding is one such process; it is repeatable, simple, neat, and allows for the placement of circuit connections close to component bodies. Because of this close joining, high-density modules are possible. In frequency-sensitive circuits, the shorter lead lengths are desirable. If a satisfactory job is done in each design area so that the product will meet all customer specifications, then the cost incurred is minimum. Factoring in cheaper or supposedly equivalent methods and materials is dangerous to the success of the product. In fact, such practices may well boomerang and raise the manufacturing costs from expensive revision and rework.

MODULAR WELDMENT

This paper is a report of one attempt to find common denominators in the area of module design. The module configuration has been called *modular weldment*, but it is more than a configuration; it is a system of integrated design and manufacture. Although the modules are designed to withstand the extremes of missile environment, the environmental integrity is achieved without the penalty of special devices. This means that modular weldment is directly applicable to aircraft, ground, and test equipment—with no cost penalty and sometimes even with a cost reduction.

Missile environments generally cover these parameters:

1. High and low temperature
2. Vacuum
3. Shock
4. Acceleration
5. Extreme vibration

Designers would generally agree that no one design will be optimum under all conditions for this kind of environment. Therefore, a design compromise must be achieved to reduce the extremes sufficiently and meet performance requirements reliably. Reliability (other than inherent component and circuit reliability) can be achieved only through a judicious selection of design approaches. One fundamental of the modular weldment design is the elimination of the following accessories:

1. Terminals
2. Stand-offs
3. Printed-wiring boards
4. Pallets
5. Base plates

The reduction in number of parts accounts for an increase in reliability because on a strictly logical basis, fewer parts equal fewer mistakes and fewer failures. This simplification of the module also lends itself to the criteria for mechanical design:

1. Reduced size
2. Reduced weight
3. Increased thermal control
4. Increased vibration/shock integrity
5. Increased accessibility
6. Increased manufacturability
7. Reduced cost

The design goals based on these criteria are:

1. To simplify the package
2. To use potting extensively (other supports eliminated)
3. To devise a definable connection method
4. To simplify structural elements

These goals were achieved for both digital and analog type of circuitry. The following module description illustrates the configuration which is shown in the IF strip in Fig. 1:

1. Resistance—welded joints between component leads and longitudinal interconnecting nickel ribbons.
2. Polyurethane foam potting compound to support both joints and components.

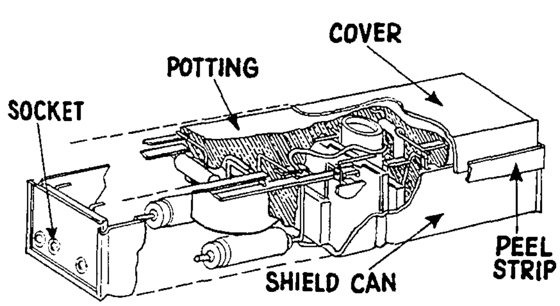

Fig. 1. Typical module configuration of modular weldment.

3. Nickel sheet shield can 0.005 in. thick to provide a tolerance-free potting mold and RFI shielding for the circuitry.
4. Coaxial-type sockets flush with, or nickel ribbon leads/pins extending from the module shield can for interconnection.
5. Shield-can cover soldered on with nickel peel-strip for ease in removing cover.
6. Provision for tuning where required through apertures in the shield can. Although it is not really a part of the module design *per se*, a soldered-tab system is essential for mounting. This system eliminates hardware and simplifies installation or removal.

The logic underlying the approaches to the module design are defined further in the chart in Fig. 2. A given group of components with 1000 connections are to be packaged by three common methods—printed-wiring board, point-to-point soldering, and modular weldment. The printed-wiring board is the standard bolted-down type that requires an insulator and spot-potting of components for vibration integrity. Pallet-type modules with potting compound encapsulating the components are comparable to the point-to-point example described. The chassis and interconnection between circuits are assumed equivalent. Point-to-point soldering simply uses terminals, stand-offs, and feed-throughs for component connection and fixturing.

Such a reduction causes one to look with a jaundiced eye at accepted methods of structure, RF shielding, vibration resistance, and connection.

When weights and volumes of modules containing 500 components (approximately 1000 connections) are examined in each of the packaging techniques, the results are as shown below. The 500 components (approximately 1.0 lb) are assumed to be similar to those used in the 24-Mc IF strip. The components themselves have an approximate volume of 4 in.^{3}.

Package Containing 500 *Components*	*Printed-Wiring Board*	*Point-to-Point*	*Modular Weldment*
Volume	32.0	18.7	6.02
Weight	3.09	2.8	1.25

#ACCESSORIES/1000 CONNECTIONS

METHOD / ITEM	PWB	POINT POINT	MODULAR WELDMENT
SOLDER	.040	.04	
1/8" BOARD	.367		
HARDWARE	.077		
EYELETS	.033		
COPPER RUNS	.040		
INSULATOR	.138		
STAND-OFFS, TERMINALS		.44	
NICKEL RIBBON			.0063
POTTING			.0217
TOTAL	.695	.48	.0280

Fig. 2. Packaging accessories for three common packaging techniques.

Analysis of these figures indicates that the printed-wiring board requires 2.09 lb to package 1 lb of components, and the point-to-point system 1.8 lb for the same amount. In contrast, modular weldment requires only 0.25 lb. The volumetric and gravimetric efficiencies are as follows:

	Printed-Wiring Board	*Point-to-Point*	*Modular Weldment*
Gravimetric	33%	36%	80%
Volumetric	12%	22%	66%

Although the modular weldment system is suitable for either analog or digital circuitry, it will be described for use with a digital module. The components used in digital circuitry (assuming low power dissipation) are generally smaller and more regular in form factor and, hence, permit higher density. This high density is better for demonstrating the effectiveness of the simplified design and manufacturing approaches. Analog circuitry is also mentioned frequently throughout the paper to show the system's flexibility.

The schematic for a single stage of shift register is shown in Fig. 3. To facilitate manufacture, testing, and maintenance, three stages are grouped in a module.

The components used are shown in Fig. 4. Figure 5 is a typical three-stage module showing the welded component configuration, foamed polyurethane potting, and nickel RFI shielding. The shift register is not operating at a 1-Mc shift rate and it is felt that shielding from electrical and magnetic radiation will ensure stability of shift rate—therefore the RFI magnetic shield can. The module contains sixty standard components, i.e., not made as specials for this application but available from catalog.

The components are arranged in four levels to simplify assembly. Figure 6

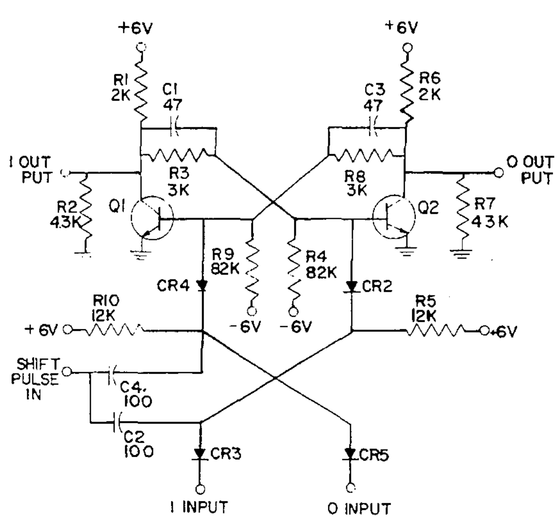

Fig. 3. Schematic of single-stage shift register.

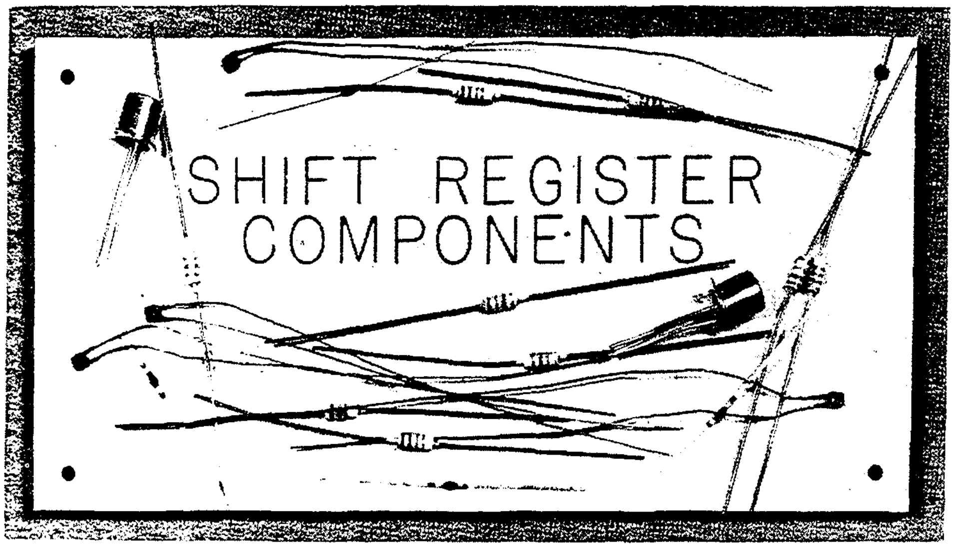

Fig. 4. Components used in shift register.

shows the four levels of a single stage on their individual welding jigs. These are merely representative. Actually, the components for three stages are placed in the jigs before further steps are taken. This figure shows the nickel ribbon interconnecting wire for the circuit. These ribbons can run the length of the module as common or bus connection or can be cut at appropriate points to perform separate circuit functions. Figure 7 is the assembly drawing for one level and Fig. 8 the assembly for the module. The four levels are assembled and welded, and intermediate ribbons are cut and inspected separately. The four levels are assembled first into two groups. Interlevel welds are made and the two major groups are assembled and interwelded as shown in the module assembly of Fig. 7. Figure 9 shows the four levels of welding jigs assembled and interwelded. Note that the necessary power and signal inputs and outputs have been brought out of the jigs at the appropriate levels to facilitate testing procedures.

The module is now electrically tested and if component changes or repairs are required, the components are accessible. This module could be potted in several ways:

1. Cut from jig—put in mold.
2. Pot in jig—destroy jig to remove module.

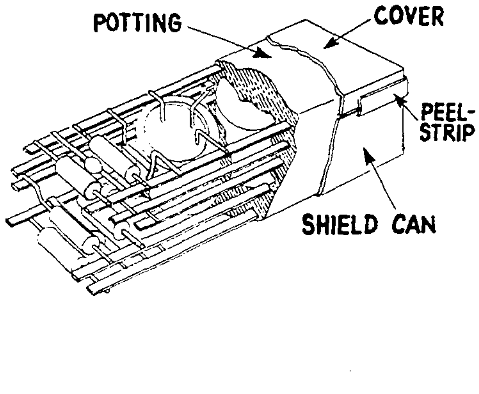

Fig. 5. Typical three-stage module configuration.

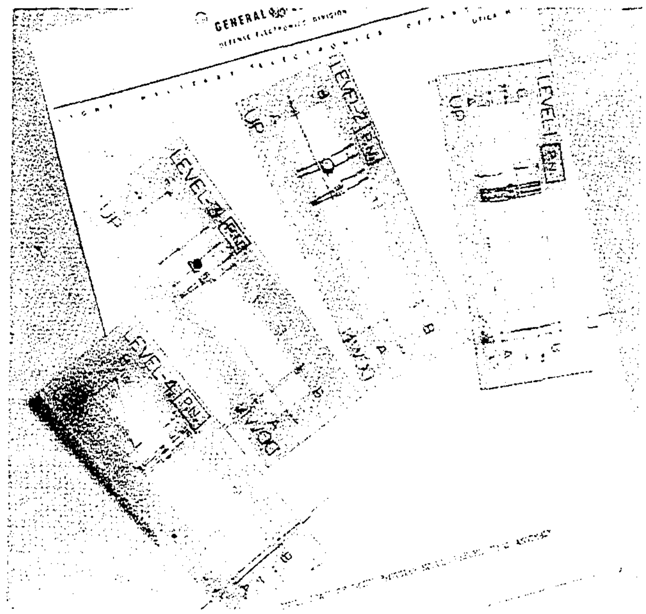

Fig. 6. Single stage of shift register module before final assembly.

3. Cut all but top level of component wires—place circuit in shield can, which would act as potting mold.
4. Form potting mold inside jigs with thin ribbon "gaskets" between the several welding jigs. The top and bottom are now sealed with metal covers.

One of the prime functions of the welding jig is to protect the components and joints during handling. The importance of this precaution to successful processing

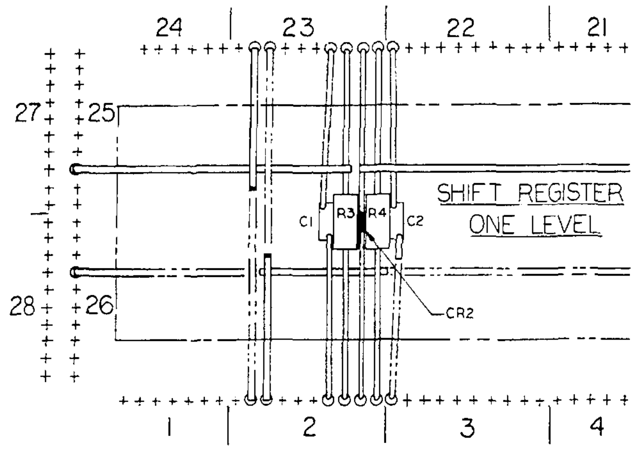

Fig. 7. Assembly drawing for one level of a shift register.

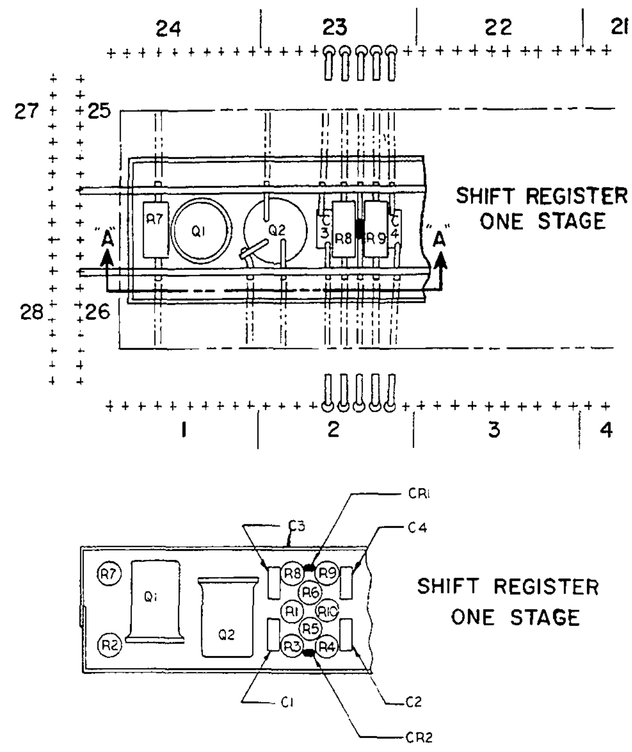

Fig. 8. Assembly drawing for the shift register module.

cannot be overemphasized. With approximately 125 connections in the three-stage shift register module, protection is a matter of concern. It would appear that potting method 1 would endanger integrity; method 2 is wasteful of jigs and complicates the mold; method 3 is quite satisfactory, provided extreme care is taken in cutting the lower levels from the assembly and in handling before insertion into the shield can. This method also is consistent with that employed in the manufacture of receiver-type circuit modules.

On the other hand, if maximum protection is paramount, then method 4 is the best technique. The "gasket" mold is first formed as shown in Fig. 10. The components in the mold cavity are potted in polyurethane foam (Fig. 11). With an appropriate high-speed saw, the module is cut from the jig outboard of the parallel nickel ribbon. During this operation the components and joints are fixtured securely by the potting compound. The input–output leads are then cut, and the module, as shown in Fig. 12, is ready for electrical test. When the necessary tests have been performed, the module is prepared for assembly to the shield can. For this process the shield can shown in Fig. 13 has the following configuration: the bottom, sides, and ends comprise a single piece, and the cover comprises another. Both pieces are prefolded and punched where necessary for lead egress.

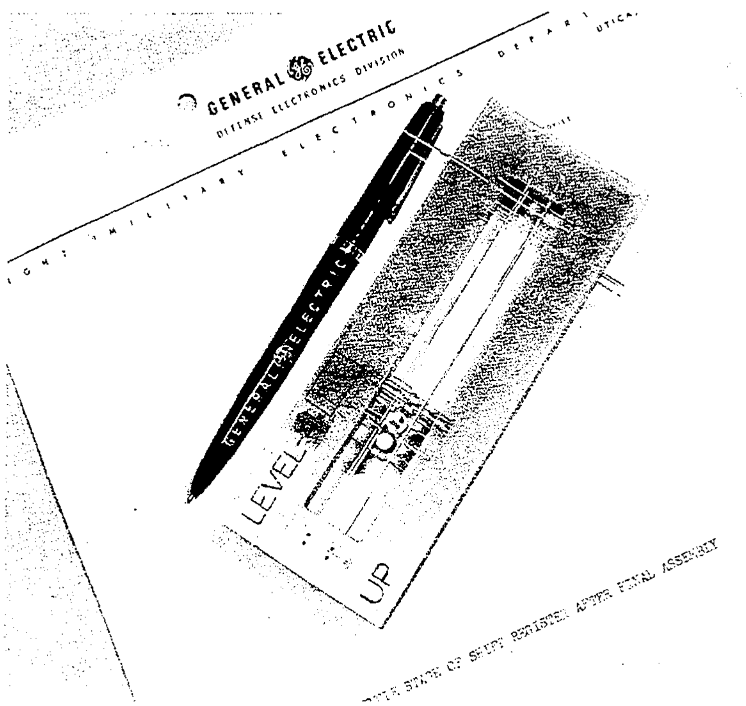

Fig. 9. Single stage of shift register after final assembly.

The exposed lead-ends in Fig. 14 on the module sides represent all of the circuit connection points not brought out of the module and are an excellent trouble-shooting aid. For this reason, the cut ends are covered with tetrafluoroethylene tape. Figure 15 shows how the shield can bottom is placed on the module. The shield can top is then assembled as shown in Fig. 16. A solderable·peel-strip is

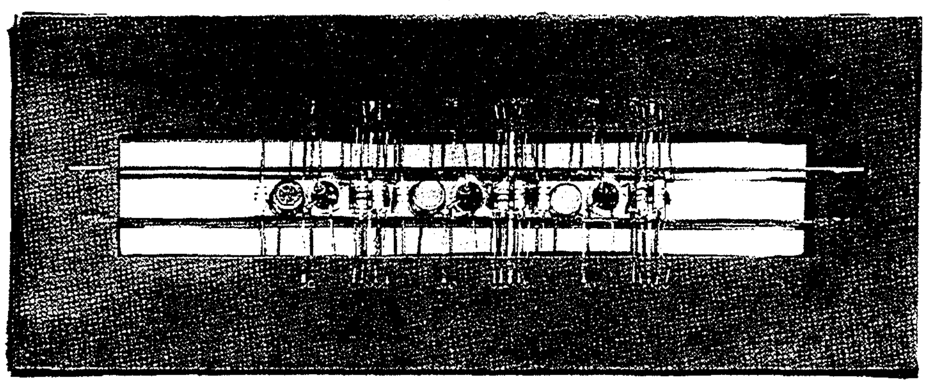

Fig. 10. Assembled components in "gasket" mold.

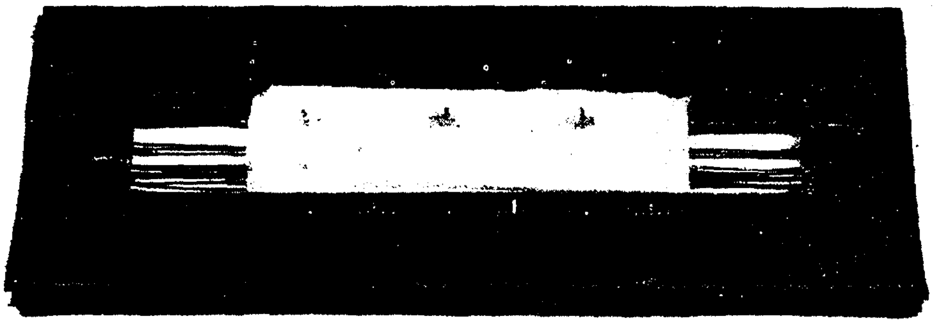

Fig. 11. Components potted in polyurethane foam.

Fig. 12. Module ready for electrical test.

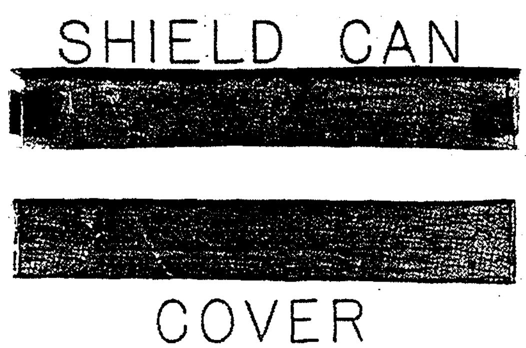

Fig. 13. Shield can showing two-piece construction. Base, sides, and ends are one piece (top of photo); cover (bottom) is another.

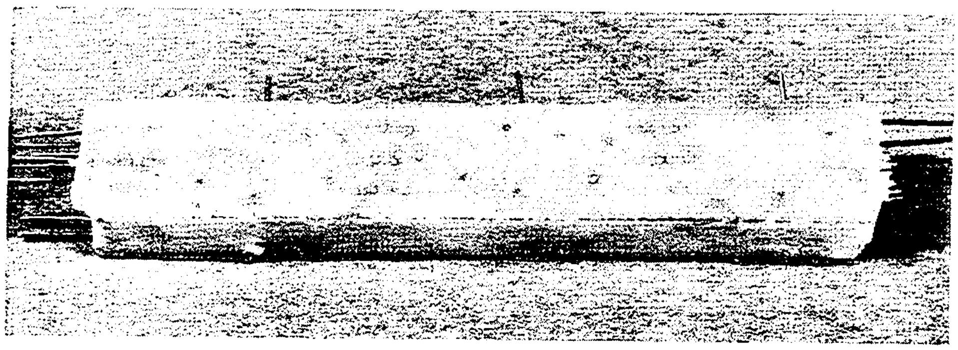

Fig. 14. Module showing exposed lead ends useful in trouble shooting.

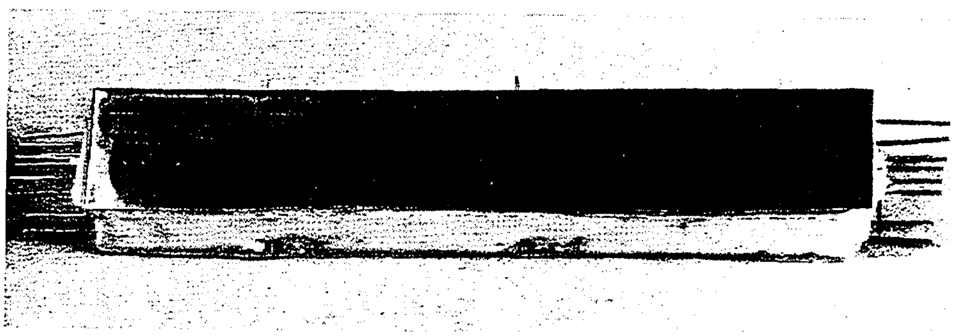

Fig. 15. Assembly of bottom of shield can to the module.

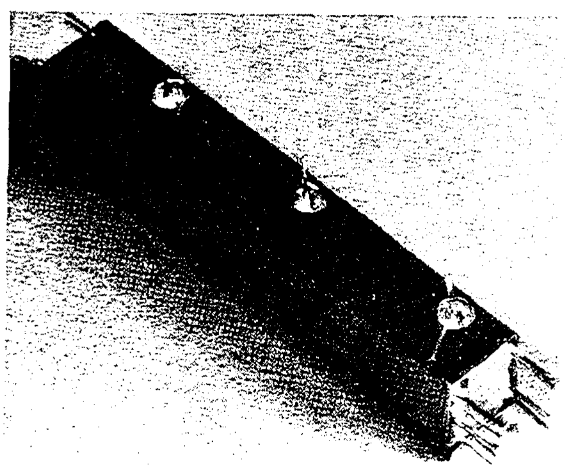

Fig. 16. Assembly of top of shield can to the module.

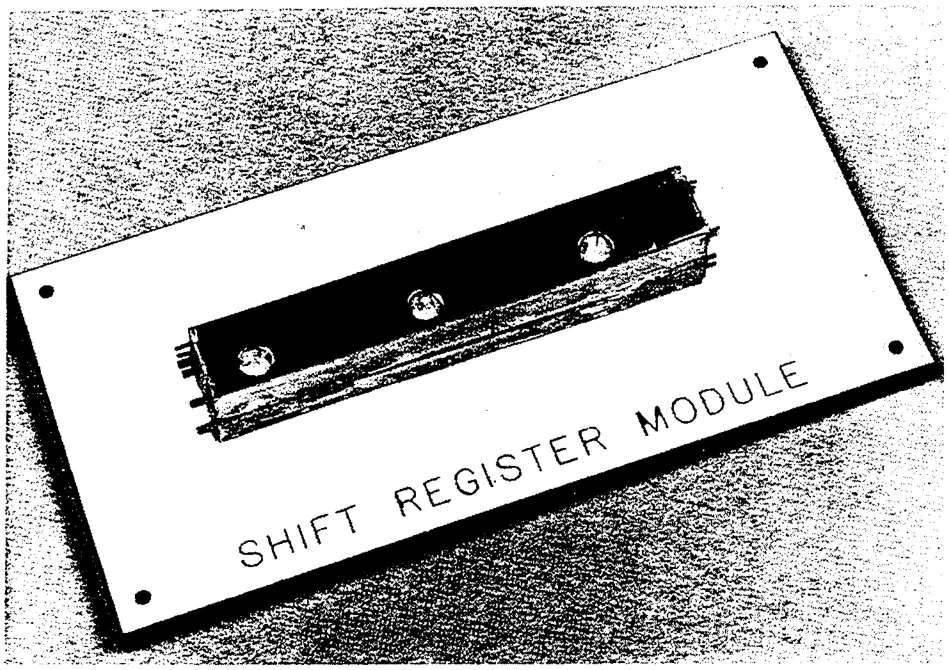

Fig. 17. Completed unit with peel-strip soldered on.

next assembled to the module, and the unit, as it appears in Fig. 17 is ready for final electrical test.

If for any reason the module must be reworked or repaired, there is an established procedure. First, the peel-strip is removed, and the halves of the can separate readily. The tape is next removed, and a point-to-point check at the exposed circuit connections reveals the faulty components. With proper masking and care a mildly abrasive spray will remove the potting compound, and the component can be replaced. Walnut dust and high-pressure air have proven to be effective in removing the potting compound without damage to the components. The procedure for reassembly is essentially the same as initial assembly.

This potting procedure applies most directly to multiple-level devices. In the case of single-level assembly, such as an IF strip, the procedure is somewhat simplified. It should be re-emphasized that the procedure for the shift register can be modified to match the procedure for single-level assembly. The compromises must be weighed for each application.

Figure 18, an example of single-level assembly, is a picture of a 24-Mc IF strip with four stages, 80-db gain, and approximately 2-Mc bandwidth. The schematic is shown in Fig. 19, and the parts used in Fig. 20. Here there are considerations of RFI and feedback to plague the designer. Logically, however, if all of the leads can be shortened to a minimum, then the radiative sources and receivers for feedback will be kept to a minimum.

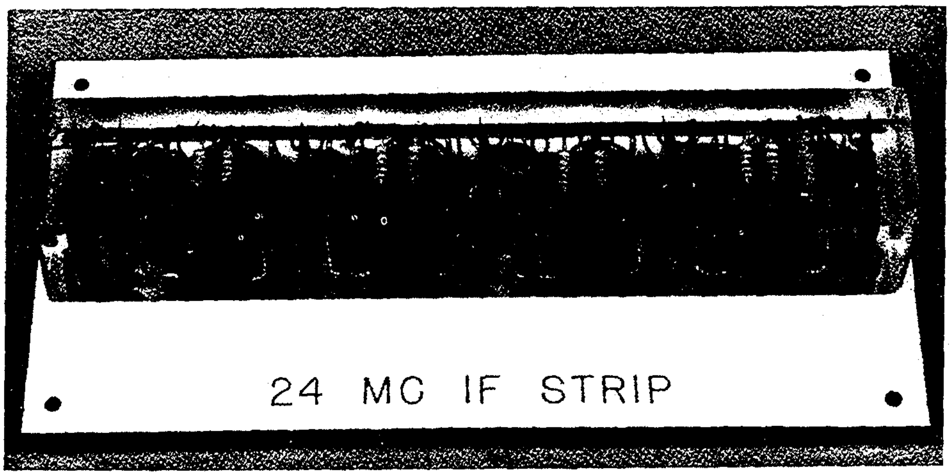

Fig. 18. Single-level assembly IF strip in encapsulant.

The stages are transformer-coupled so provision for tuning after final assembly must be provided. This type of circuitry is also susceptible to short-term, electromagnetic pulse radiation; the nickel shield can, described in the shift-register discussion, is the answer to both the RFI and magnetic problems. The stages are separated by nickel shields to provide a measure of feedback reduction. After welding and circuit separation (as in the shift register), the shield can, with the coupling transformers permanently attached, is assembled to the circuit (see Fig. 21). Note here that only four ribbons are required as bus and intermediate wiring. The intermediate shields fit in grooves in the can and are soldered in position. After the transformers are welded into the circuit, the IF strip is ready for test. Again, because the components are still accessible, any repair can be made. In this case, however, an electrical check before the shield can is assembled saves some manipulation.

The module, still protected by the welding jig, is placed in a mold, and the circuit is potted in foam. (Polyurethane is used here specifically for its dielectric

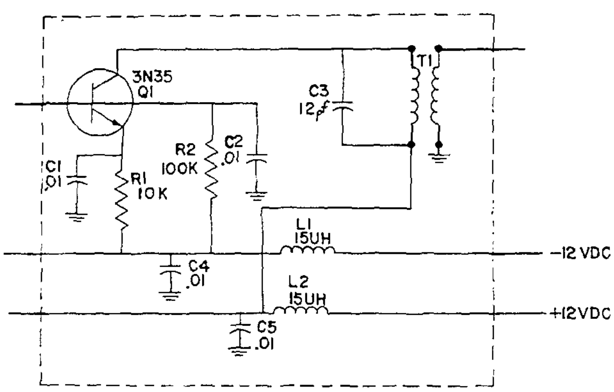

Fig. 19. Schematic of IF strip shown in Fig. 18.

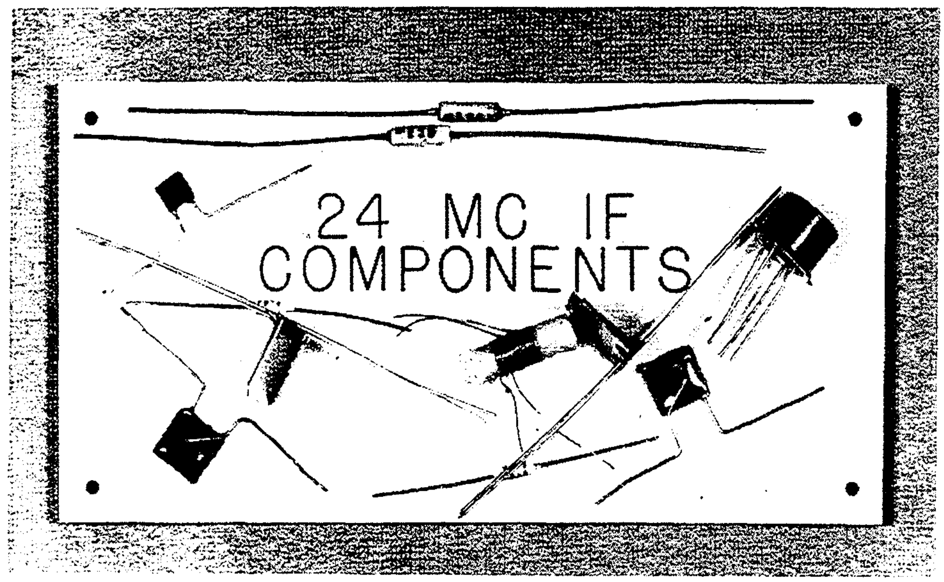

Fig. 20. Components from IF strip in Fig. 18.

constant, which approximates that of air.) The potted module is shown in Fig. 22.

The component lead wires extending from the module sides are cut off, outboard of the longitudinal nickel ribbons, and the input–output leads are clipped off at the welding jig. The module, with tetrafluoroethylene tape covering the exposed lead ends, is shown in Fig. 23. The cover is attached to the module with a solderable peel-strip, and it is ready for final test. In the completed module in Fig. 18, note that the tuning access holes for the coupling transformers are visible.

Figure 24 shows one possible method of mounting the completed module. A preformed nickel sheet is soldered to the mounting surface. Modules are placed on each side of the sheet, and the small tabs shown are soldered to the module. To remove a module, only the tabs on its surface need be unsoldered. Adjacent modules are not disturbed.

No specific mention has been made thus far of the provision for interconnecting modules. This step must be hypothesized because at present there is no direct package application. If the modules are to be plugged in, then at assembly, suitable pins, extending from the can, must be welded into the circuit as shown in Fig. 23. Because these are fixtured much the same as components, they present no particular assembly problem. They are a problem during potting, but they can be accommodated with grooves in the mold. If the module is to be plugged into, then sockets consistent with the component sizes are fixtured and assembled the same way as the pins.

If the application permits, the modules can be welded into some interconnecting wire configuration such as multiple ribbons or wires embedded in a dielectric. In this event, nickel ribbon extending from the module is satisfactory.

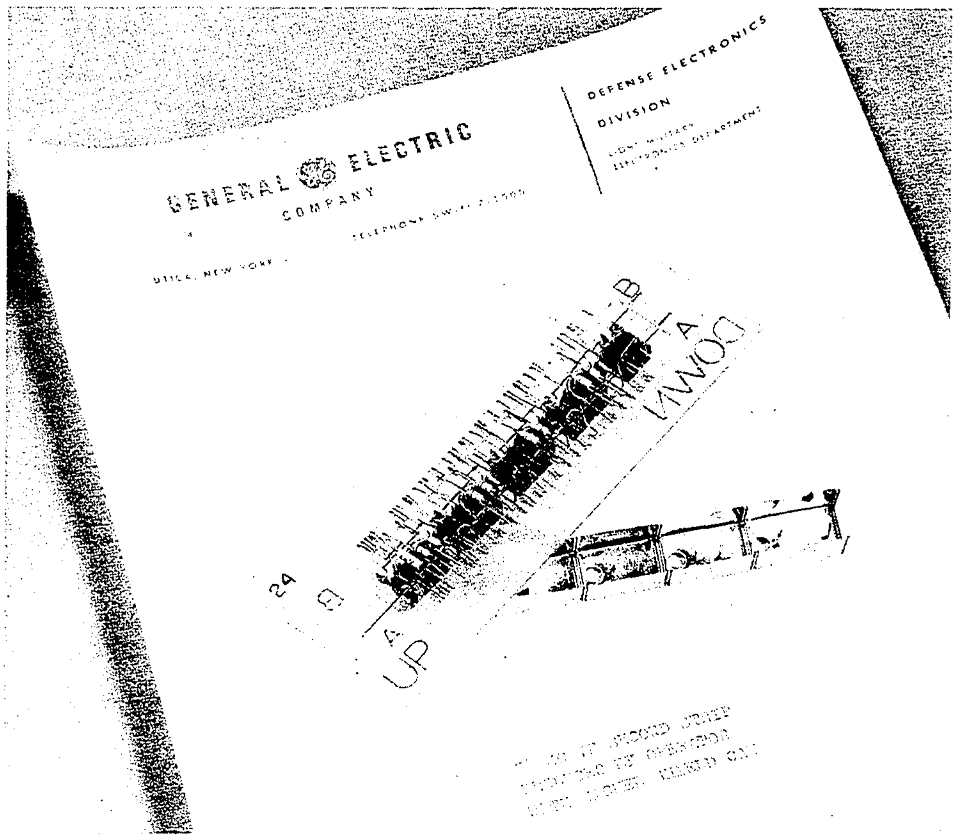

Fig. 21. IF strip shown with nickel shield can.

CONCLUSION

At numerous conferences as well as in the literature volumetric efficiencies have been bandied about for all to argue over. To talk intelligently about this subject some common ground must be established. First, the volume of a circuit must be referenced to the power dissipation and electrical requirements. Second, it must be referenced to the cost. Does the application preclude the use of very small components? Third, is the fact of the application taken into account, i.e., how is the module connected or mounted? Fourth, if packaging schemes are to be compared are these three factors identical?

The aim of the work described in this paper is to achieve the minimum volume consistent with reasonable ease of manufacture, flexibility of design, simplification of product, high repeatability, and reliability. The circuits use standard catalog components. The power dissipation is low. Cost was not the prime objective though it has been kept in mind not only in components but in the entire design–manufacture cycle.

The shift register dissipated 40 mw per stage or 120 mw per three-stage

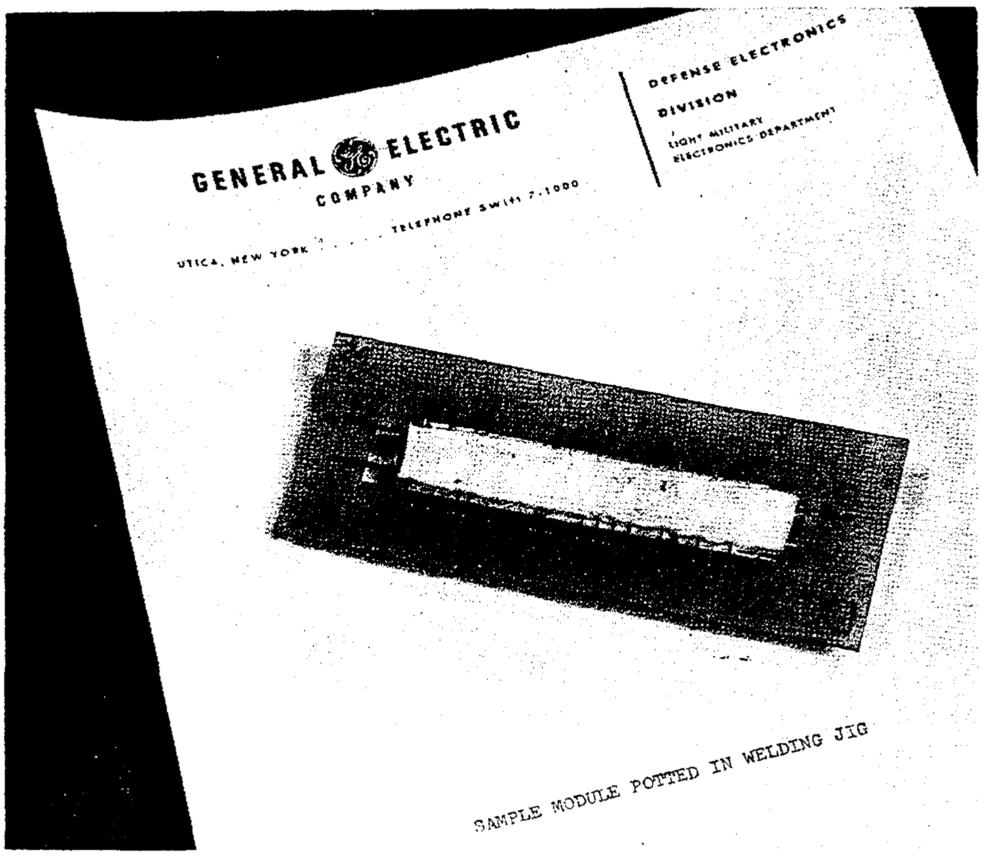

Fig. 22. Sample module potted in welding jig.

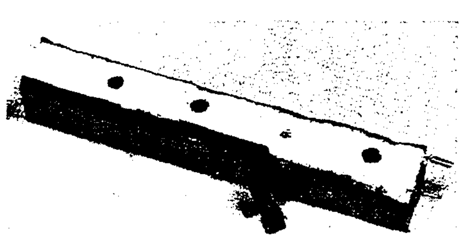

Fig. 23. Module with cover attached. Note solderable peel-strip.

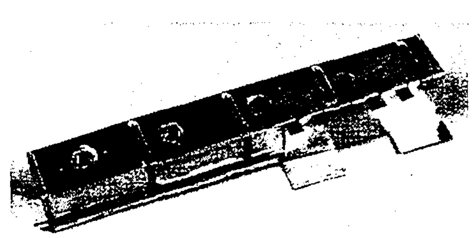

Fig. 24. Potential mounting technique with which preformed nickel sheet can be soldered to the mounting surface.

module. Temperature tests have indicated that without shielding, the volume of polyurethane foam does not represent a heat barrier. Profiles show satisfactory operation at rated temperatures with the components density achieved. The volume per stage of twenty components packaged in Modular Weldment is 0.07 in.^{3}. Including potting compound it is $0.31 \times 0.312 \times 0.8$ in. This figures theoretically to 256 components/in.^{3} or 444,000 components/ft^3; however, this is a three-stage module and there must be provision for interconnection to the next module (and/or the preceding module). If interconnection by welding to the extended nickel ribbon is assumed, a maximum of 0.050 in. per module end is required. The module has a total volume of 0.236 in.^{3}, and the components-per-cubic-inch figure reduces to 254; components per cubic foot is down to 439,000.

By reducing the transistor case size (and, incidentally, incurring five times the cost of the present transistor), the module volume can be reduced to approximately 0.12 in.^{3}, and the component count, including potting and interconnections, goes up to 860,000 per ft^3.

Carrying this one step further, the same circuit using microminiature transistors, at more than ten times the cost of the present type, would reduce module volume to 0.08 in.^{3} and would raise the component count to approximately 1,300,000 including potting and interconnections. If the standard resistors and capacitors are replaced with microminiature devices, the volume of the module is reduced to 0.03 in.^{3}, and the components per cubic foot count climbs to more than 3,000,000! In the process, however, the manufacturing technique is put under a microscope, and the manufacturing costs go up accordingly. Component costs also skyrocket. If it is mandatory that minimum volume be achieved, then the components and processes are available. In short, the application will determine the density required.

The high-frequency amplifier described here has a density, including interconnections (extended ribbon), of 65 components/in.^{3} or 112,320 components/ft^3. By replacing the transistor, the density can be increased to perhaps 155,000. Going to microminiature resistors would not help appreciably since the remaining circuit elements are large by virtue of electrical function. It is possible to work an amplifier such as this up to around 200,000 components/ft^3; however, this has not been done to date, and electrical operation, therefore, has not been proven.

DISCUSSION

Q. (Roger Gaefcke, AC Spark Plug, El Segundo, Calif.) With a foam-type potting compound how did you provide for heat removal?

A. I have run a considerable number of tests on modules—I've shown some of them here today—where we have inserted thermocouples at what we considered to be the hot points and also at any other points that the technician could find. I have not found to date that the amount of lock foam that I allow in the interstices is sufficient to provide a heat barrier. My problem is somewhat the other way around in that the environment that we are working to here is 125°C, so that if I put this module, say, the shift register, which is about 40 mw per stage, on a piece of metal which is at 125°C it comes to 125°C; there is no barrier.

Q. (Ed Cormier, General Dynamics/Astronautics, San Diego, Calif.) Did you environmentally test this unit? I am interested specifically in vibration and random noise.

A. I have not—it is like bringing coals to Newcastle. We have been working with lock foam potted modules for a number of years and they have flown successfully on many missile flights and I would say several hundred complete systems have been vibrated as such in both sinusoidal and random and we have not had any failures of potted modules. So when I propose to someone that I spend some money to shake these potted modules they ask me why. We will shake them in the system.

Q. (Joe Ritter, Electronic Modules, Timonium, Md.) Was it a system requirement that these modules be repairable, because it looks like you have gone into the effort of making it repairable, but it isn't really repairable? If you have a bad component in there it wouldn't even pay to try to fix it.

A. I don't know that I agree with you that it wouldn't be worth the effort, since we have repaired these modules. But it is not a system requirement to repair the modules. I am well aware that regardless of what the requirement is, if manufacturing has a problem they will try to correct it, and if I make the module design so that they can tear the whole thing apart in order to get at what they want to do, whether I want them to do it or not, I am going to be in trouble. So I have made it as easy as possible, but I don't recommend it.

Q. (Bob Mercer, Space Technology Labs., Redondo Beach, Calif.) I was wondering if you had made a time study to cut down the production standing points you have for all these various assemblies. It seems like you have four or five weld assembly areas before you go to encapsulation. Has this been compared to the standard cordwood type of module construction?

A. It has been compared to it. Unfortunately, no one is willing to compare a system such as this. This came, as you may note from the paper, from an advanced development study for the Air Force. Without a product in the factory, or without a product going into the factory, no one is particularly willing to take on an official position so that it has not been declared officially, but I think that the time that I have spent on this has convinced me that what you are saying is not necessarily so. The time that is taken by the design of the module overshadows the time that it takes to build the module, although I have not tried to present either in the paper or here any actual figures and I don't intend to.

Q. (Ed Raymund, Hughes Vacuum Tube Products, Maderi Beach, Fla.) This is the first paper that I have heard here where shielding was mentioned at any length, but I have seen a number of instances lately, especially in some of the analog circuits, where shielding is quite important. I wonder if you would like to elaborate just a little bit as to: first, why you went into shielding and why all of your modules are shielded. Second, what degree of isolation are you attempting to obtain with your shielding, and how effective has the nickel been as a shield as compared with other shielding materials such as Co-Netic or Mumetal?

A. I touched upon the reason for shielding. The frequency of the module that I have shown you here is quite low compared to the frequencies that are running around in a given missile guidance beacon, which I am most familiar with. And as I mentioned, these frequencies are generally harmonics or subharmonics. Therefore, we have always shielded, and one of our major problems has been the interaction between modules and circuits. Now, prior to the development that I have been involved with here, we have used rather thick aluminum chassis to do the shielding. Not too many years ago it was a heavy aluminum casting. My attempt here is to ensure that we have, not only RFI shielding, but magnetic shielding as well, so I chose nickel. I can't say that nickel is more effective than Co-Netic materials. We didn't use them because nickel was, to our minds, much easier to fabricate and I believe quite a bit cheaper. It is sufficient for our needs. Now as to the db of shielding attainable, I am afraid I don't remember the figures exactly. The decoupling, particularly on the power lines, is quite important, as a matter of fact we have found that it is not only sufficient to shield the modules and to decouple within the modules or within the stages, but I'm coming to the point where I'm going to use co-ax connections between modules for all leads. And if the modules are operating at different frequencies referred to one oscillator the problem is tremendous, so that we have tried to decouple and we have tried to shield and, particularly because of the coupling transformers, we have tried to shield magnetically. And incidentally these circuits must be tuned after they are packaged.

A Composite Approach for Packaging Interim Analog Electronics

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Criteria for a practical approach to miniaturization methods as a composite of existing and new techniques are advanced, and their successful application is demonstrated on hand of a specific example employing a circuit representative of a typical low-frequency analog packaging situation.

NEVER BEFORE in the history of electronic technology has the quest for miniaturization been more avidly pursued than at present. The Advanced Packaging Group of the Product Engineering Department operating under Independent Development Program funding has endeavored during the calendar year 1961 to enhance the position of Raytheon Company, Missile and Space Division, in this specialty. Described herein is one of the products of this effort.

Early in the year considerable time was devoted to acquainting ourselves with the many techniques being investigated by others in the industry. Notable among these were both soldered and welded "cordwood," pellet-component, thin-film, and molecular electronics. Each of these techniques shows particular promise for special applications. For example, thin-film procedures are ideally suited for relatively simple circuit configurations which recur in sufficiently large quantities to justify the complexity and cost of multiple masking and very closely controlled fabrication processes. It is ideally suited to digital computer work. "Cordwood" techniques permit maximum densities employing present-generation component of known reliability. Pelletized components offer challenging potentialities but further progress is needed to qualify presently available components and to expand the variety of items available in pelletized form.

We consider molecular electronics for analog application as being "just beyond the horizon" and will, for the present, watch and wait. Please understand, however, that in this I speak only for the Product Engineering Section of Missile and Space Division. Other sections of Raytheon Company are very actively engaged in molecular electronics development.

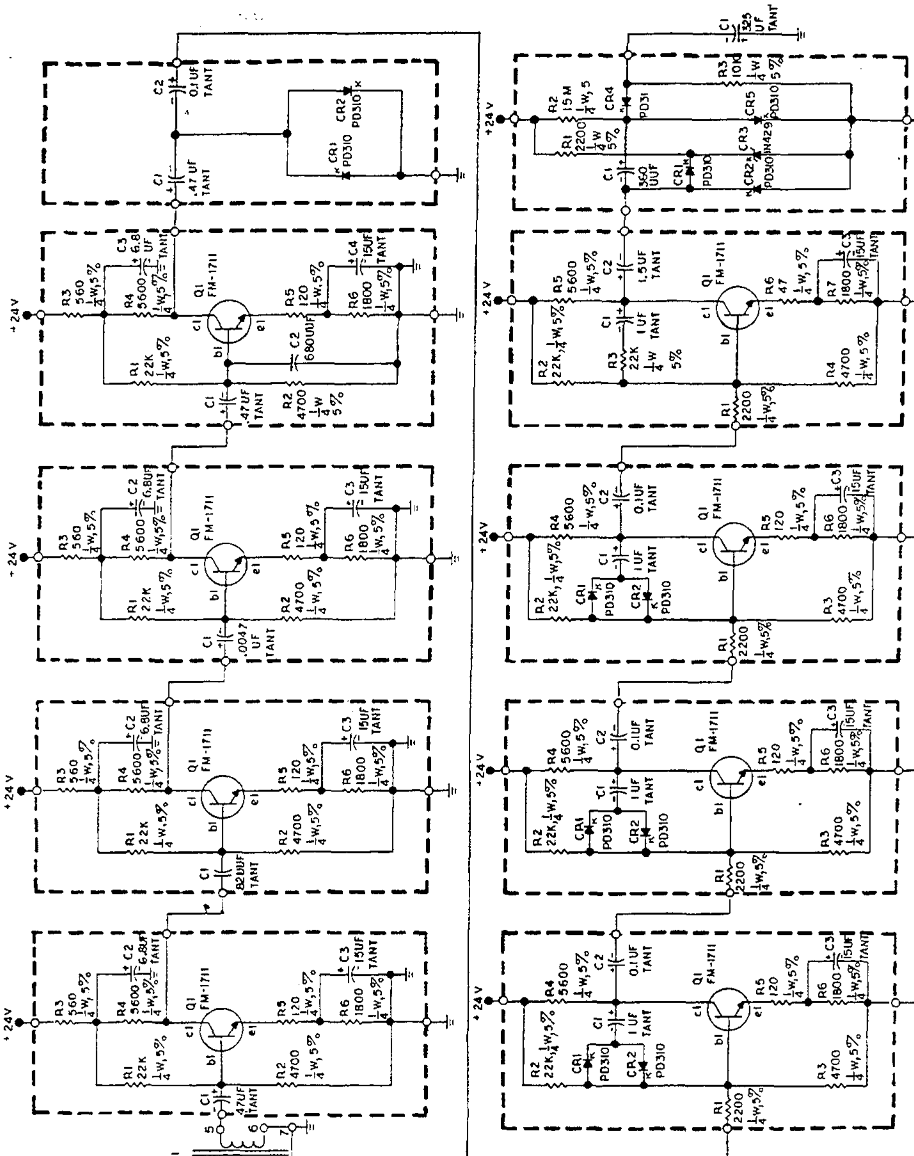
In this discussion we are concerned primarily with the application of miniaturization methods to analog-type circuits. In contrast to the popular habit of prognosticating ever-increasing populations of circuit elements contained within ever-decreasing perimeters of space, we have taken an unspectacular approach built upon the following considerations:

1. The smallest components of known reliability presently available should be employed.
2. A composite design concept should be used, attempting to intermingle the several aforementioned techniques as the properties of each best suit the needs.
3. Modularization should be carried to a level of cost, complexity, and minimum interconnection consistent with an economic throw-away philosophy. Insofar as possible, modules should coincide with natural circuit "break-away" boundaries.
4. Where possible, modules should be individually testable, preferably as a functional entity.
5. The design concept should permit the incorporation of evolutional circuit changes without requiring radical upheaval of the overall complex, or extreme expense resulting from scrapped precision tooling.
6. Where possible, full consideration should be given to the evolution of a design capable in whole or in part of automation.
7. Application to a wide variety of end usage (submarine, surface, airborne, space, etc.) should be possible.
8. From the coldly practical standpoint, the approach must be governed by feasibility within the limitations of cost, availability, reliability, and adaptability to future improvement.

The schematic diagram of Fig. 1 represents a video amplifier originally developed for a prototype radar altimeter. We arbitrarily selected this circuit as representative of a typical low-frequency analog packaging situation. It contains a comparatively bulky input transformer, capacitors having values such that use of high-K ceramics or deposited elements are unthinkable, and the usual resistors and active solid state circuit elements. Note that the dashed enclosure lines divide the total schematic into ten "natural circuit break" modules. None has more than twelve components, nor more than four external connections.

Figure 2 shows the original cordwood assembly compared to a 1-in. cube. The torroidal input transformer—at the right side of the assembly—dictated the minimum separation of the parallel panels. Somewhat greater density could have resulted had the transformer been excluded from the complex. In any event, throw-away cost for the final cast-in-resin assembly would have been quite high. The total volume is 5.3 in.^{3}. The parts complement is slightly over 100.

As an initial exercise in size reduction, the video amplifier was repackaged as indicated in Fig. 3. Ten individual modules were assembled each containing components as contained within the dashed-line module confines of the schematic (see Fig. 1). The input transformer was temporarily set aside and maximum effort was expended in producing cordwood modules as small as the individual components would permit. The resultant complex, assembled to a parent interconnecting panel, occupies 2.4 in.^{3} of space. Even considering the fact that the input



VIDEO AMPLIFIER

Fig. 1. Schematic diagram of video amplifier.

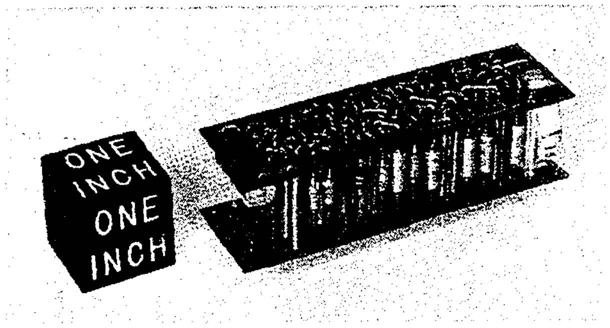


Fig. 2. Original cordwood assembly.

transformer is excluded, this represents a significant size reduction from the original design. Economic throw-away of any individual module is now practical should a failure occur. Four individual modules are shown in Fig. 4.

Encouraged by the initial reduction accomplished using lead-type components we now probed possibilities for further reduction either by mixing techniques or by further decreasing component sizes.

Reference to the schematic will show that very little further reduction of capacitor size may be expected within the defined values and voltage ratings. And, unfortunately, the capacitors account for the bulk of the package.

The resistors, on the other hand, offer several alternate choices. They could be procured as uncased units, film or screen deposited as a group on substrates, or applied as leadless pellets. The latter method was chosen for reasons to be explained later.

Diode size could be reduced significantly by going to the small PSI units. We decided to stay with the TO-47 cased transistors rather than change to smaller units for a very practical reason. The TO-47 units were on hand, and time and funds were limited.

The following illustrates a composite approach to further reduction of the

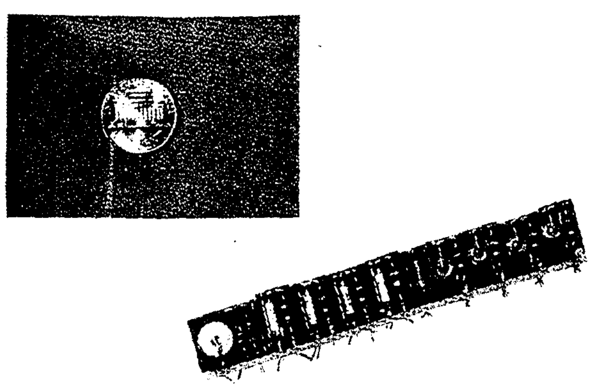


Fig. 3. Miniature cordwood modular video.

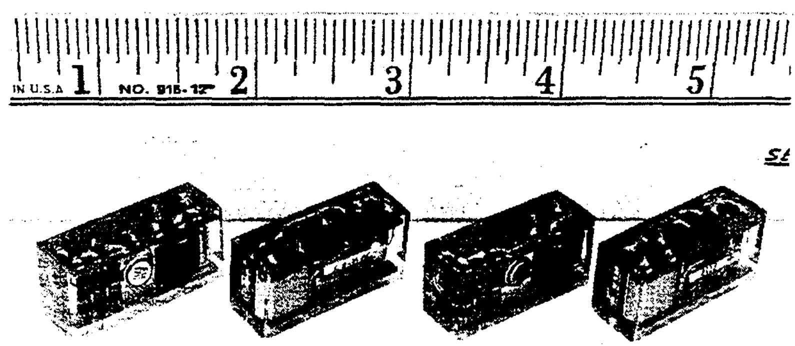


Fig. 4. Miniature cordwood modules.

small cordwood module previously shown. It satisfies many of the considerations listed as objectives. It does not represent a panacea, nor is it intended to.

Figures 5 and 6 show typical chip modules, assembled with pellet resistors.

Each module is keyed, either by its physical thickness (its only major dimensional variable) or by its tab locations to prevent error in overall assembly to the parent interconnection boards. As typical modules for this or some other application each is easily over-plated for individual electrostatic shielding. The choice of casting material can accomplish low weight or improved thermal conductivity, as required.

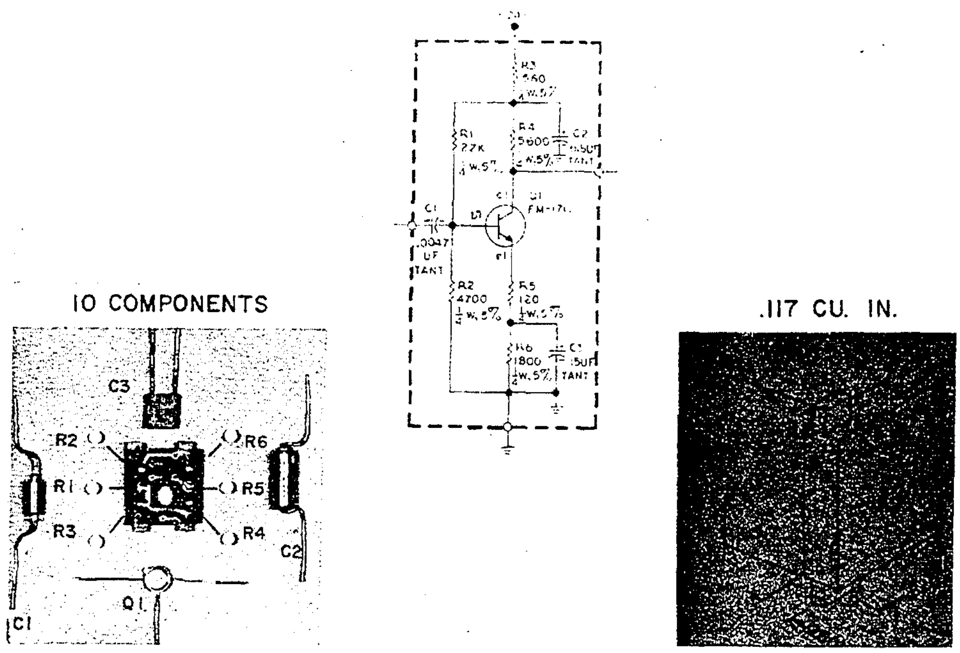


Fig. 5. Typical amplifier stage.

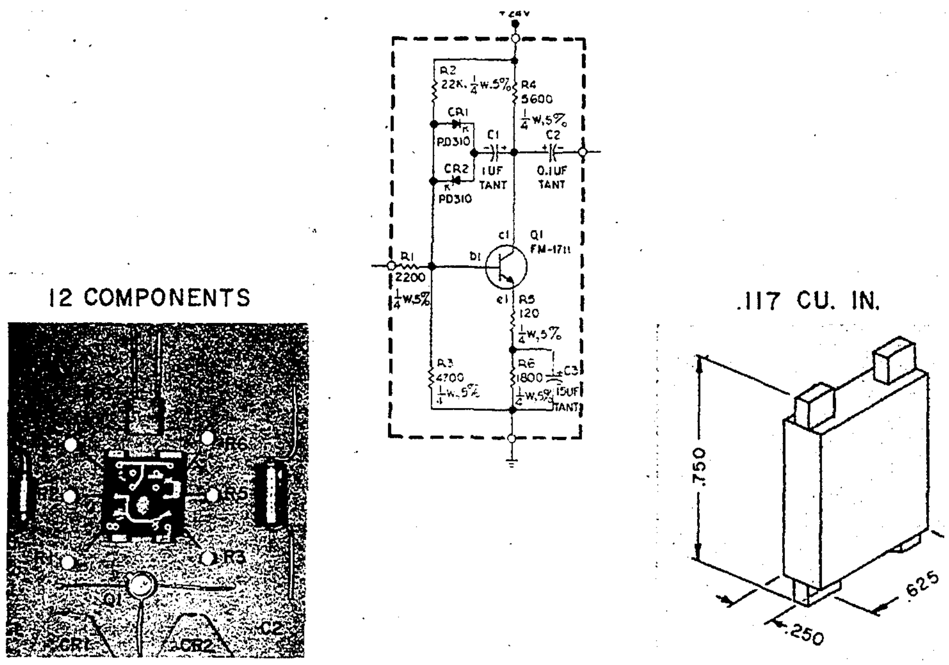


Fig. 6. Typical counter stage.

Certain of the selected components are not presently supported by reliability data, notably the pelletized resistors. It is felt, however, that in the very near future these will be qualified. In concept they are logical. Close-fitted into their retaining substrate, they become one with it, neither extending beyond its limits nor consisting of extraneous material. (The total mass performs the primary function, i.e., is the resistance element.) Where power dissipation is a factor, substrates of high thermal efficiency can provide improved transfer of heat generated within the resistance element (unlike conventional axial lead resistors, wrapped in their thermally insulating plastic shells and dependent in large part upon their axial leads for heat egress). In contrast to deposited-on-substrate film resistors, they are economically tolerant of evolutional circuit changes and pretestable as a discrete circuit element. They are adaptable to automated assembly. The practical trade-offs are larger size and inflexible—though uniform—configuration as compared, for example, with substrate-deposited thin-film resistance elements.

Pelletized capacitors were not employed in this representative packaging exercise. Reference to the schematic will show that most capacitors were of such value that it was more feasible to use standard tantalum units of known reliability at this time. This should not preclude the employment of smaller or pelletized substitutes at a later date when reliability, availability, and cost factors are more favorable. Figure 7 shows ten modules coordinated to comprise the full amplifier complex.

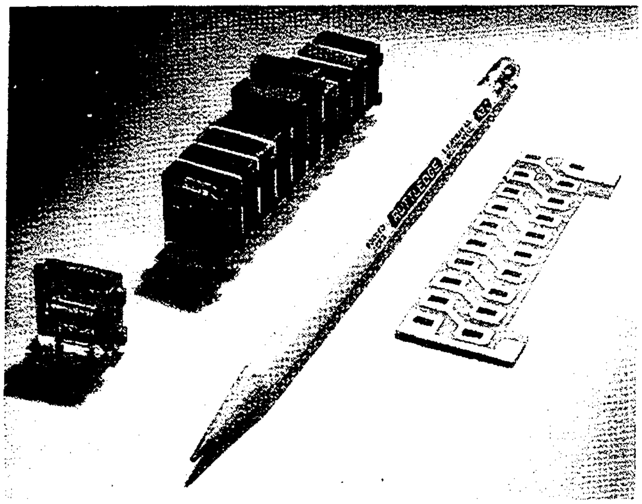


Fig. 7. Chip module video.

The overall integration, in this case, is obtained by insertion of the modules into two mutually parallel "parent" wiring/interconnecting panels, which in turn carry the input/output/supply voltage terminations on to the next generation of system connections. Should the intended application indicate the use of "pluggable" assemblies, this could be effected within the existing format. (Tabs might have to be somewhat longer.)

The assembly, as shown, includes an aluminum thermal baffle to accomplish heating or cooling as required. It adds approximately $\frac{1}{2}$ in.^{3} and $\frac{3}{4}$ oz to the overall size and weight. Without the baffle, to make a comparison with the previously described unit, it has a volume of approximately 1.2 in.^{3}. This represents a reduction of 2:1.

Rather than compromise the efficiency of this particular packaging format, the input torroidal transformer and the large-value output integrating capacitor are considered separately and not included. Presumably, this situation will be typical of many analog circuits with incompatible circuit elements requiring special treatment.

For example, in packaging electronic systems for missile applications the designer is rarely allowed the luxury of clean volumetric configurations. Much more frequently the available space is inclined to be a conic solid, possibly with a curved rectangular solid encroaching at some inconvenient location. It requires uncommon ingenuity to integrate the several component configurations inherent with most analog circuitry in a manner that will efficiently utilize such hostile dimensions. Our approach, therefore, has been one of attempting to integrate such circuit elements as have compatible dimensions and configurations. Those nonconforming elements we consider separately. These are the items we attempt to apply jig-saw-puzzle-fashion to populate the random available voids.

As is the case with most microelectronics packaging, the formidable aspect of the technique is interconnections. The initial proponents of pelletized components employed conductive cements to bridge the gap between their printed circuit interwiring patterns and the pellets. Initially this was a necessity since the end caps of the pellets were themselves a conductive paint and did not permit soldering or welding.

It is our belief that conductive cements do not insure a confidence level consistent with good military practice. Paradoxically, the loaded resins exhibiting the lowest resistivities have the poorest bond strengths.

Fortunately, later-generation pellets have end caps which are solderable. There are still some notable exceptions, but we understand that efforts are being made to bring these into line.

Figure 8 illustrates an interim approach to interconnect the components of our circuit modules. Appropriate wiring patterns are etched onto both sides of a high-temperature epoxy–glass laminate substrate (initially copper-clad on both sides with 2-oz foil). Tabs are so located as to overhang the six areas in which pellet holes will be drilled. The tabs are lifted and folded back clear of the hole locations to permit the jig-drilling of these holes. Pellets are inserted and the tabs are folded back over the pellet ends and soldered to them.

It is vital to state at this time that our experience has demonstrated the need for careful temperature control of the soldering instrument. For instance, composition-type resistor pellets have shown resistance variations as great as 30% when unregulated soldering irons were used. By attaching a thermocouple in intimate relationship to the iron tip and controlling the temperature close to 200°C (392°F), changes no greater than 5% are attainable. Incidentally, the Mallory people have

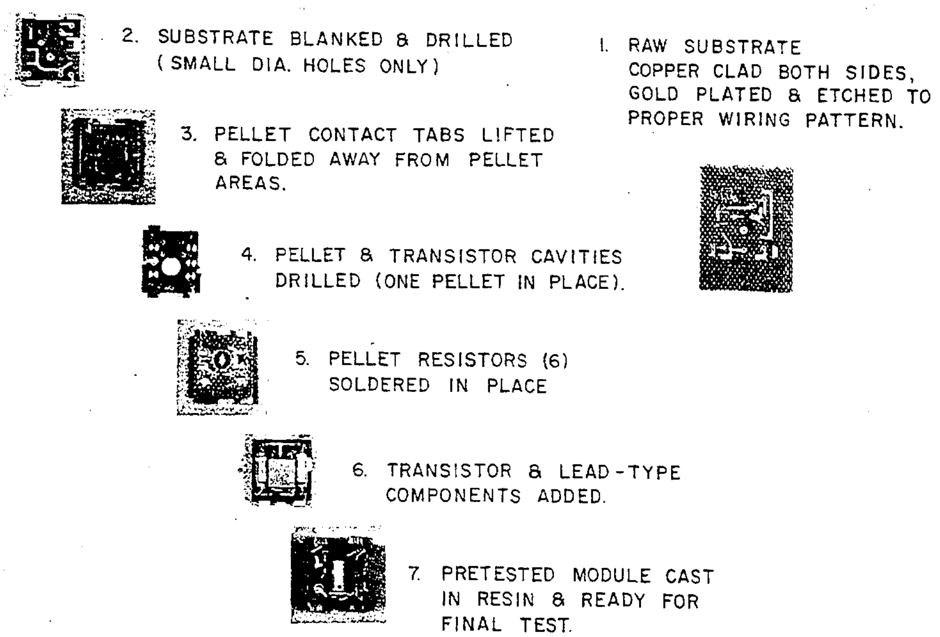


Fig. 8. Interim assembly sequence.

indicated that conditioning of composition resistor pellets at 180°C or so for a five-minute period, prior to soldering, aids in preventing permanent value changes resulting from thermal shock.

Transistors, diodes, and lead-type capacitors are hand-installed. Subsequent to initial electrical testing, the modules are separately cast in resin, the specific material being determined by the end usage requirements.

A thin conformal dip-coating of resilient RTV silicone material is desirable prior to final casting in rigid resin.

Cordwood techniques permit the simultaneous soldering of all connections on a given sandwich board. As stated previously in this paper, one prime consideration was the adaptability to automation. We therefore sought a method which would permit the preloading of a substrate with pellets and subsequent application of the wiring. Ideally all connections should be effected in one operation. How can this be done?

1. Conductive paints or cements can be applied through screens.
2. Sputtered or vacuum-evaporated metal films can be deposited through suitable masks.
3. Etched or plated foil wiring patterns can be applied to substrates, with bridging accomplished with conductive cements.

While there are undoubtedly other methods, those mentioned are certainly the most probable. However, each, for one reason or another, did not quite satisfy our requirements.

It was theorized that a new approach might be in order. Suppose a printed wiring configuration were to be etched from a supported copper foil and subsequently transferred as an overlay on top of a pellet-component-loaded substrate. Assume next that this foil pattern, by the application of heat, could be simultaneously bonded to the substrate and soldered to the pellet contact surfaces. This conjecture has certain appealing aspects.

Our plastics laboratory was contacted to probe the feasibility of implementing such a system. It was decided to employ a teflon film of 0.010-in. thickness as the supporting medium. This film could be processed as a continuous strip, identical in dimension to a 35-mm photographic film, complete with sprocket perforations.

Next, a bonding resin could be selected to bond the copper foil to the film having properties such that the application of heat, sufficient to effect a solder bond, would reduce its adhesive strength to a point where the copper pattern could be easily separated from the teflon.

Coincidentally a "B" stage resin for precoating the substrate would be selected which could be "kicked over" with the same degree of heat to effect a good bond securing the released foil pattern to the substrate.

The critical temperature for the simultaneous performance of these operations is in the region of 400°F (200°C). Tin/lead alloy solders, of the type employed, fuse in this range. Also, experience has shown that application of temperatures much in excess of this effects resistance value changes in the composition-type pellet resistors employed. It is desirable to keep the heat cycle to the absolute minimum necessary to perform the required functions; a period not in excess of 15 sec was the goal.

The following illustrates the support effort accomplished by the plastics laboratory.

Initial experiments were conducted with short lengths of teflon film rather than with continuous strips (7- or 8-in. lengths). No sprocket holes were provided (see Fig. 9).

Both precoated substrates and separate supported "B" stage resin films were investigated to effect the permanent bond. Shown in the illustration is the separate supported film. It has the undesirable feature of requiring prepunching in area where solder connections must be made; otherwise the resin film would quite obviously make the solder fusion impossible.

Figure 10 shows our plastics laboratory technician operating the "jury rig" concocted to evaluate the transfer technique.

The transfer head consists of an offset soldering iron, reoperated by the

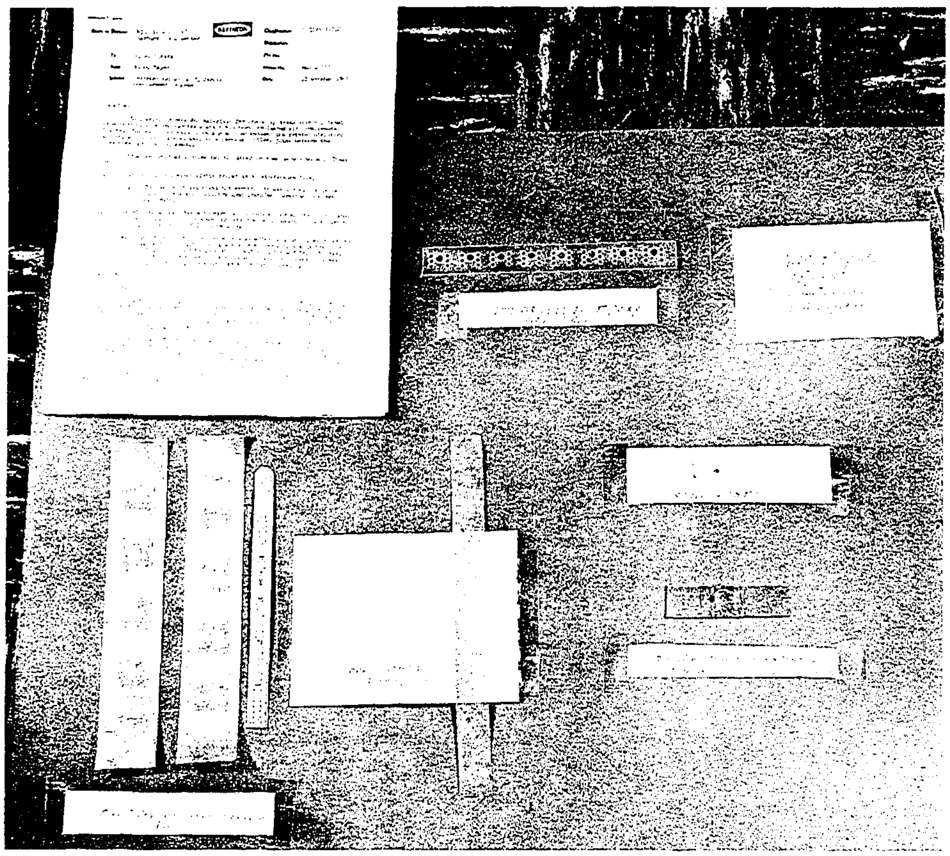


Fig. 9. Circuit transfer process.

Fig. 10. Jury rig for experimental transfer.

addition of an extension to permit its placement in the drill press chuck. This, incidentally, happened to be the most readily available arbor press. We are still speculating as to the chaotic situation which would have resulted had someone inadvertently turned on the drill.

A plated copper platten is substituted for the usual soldering iron tip. It is square and flat, having a transverse hole drilled near its interface for the insertion of a thermocouple. Note the variable transformer to the technician's left, used to control the platten temperature. The Brown recorder behind the operator is indicating slightly over 400°F. For an automated counterpart it would be desirable to provide a momentary voltage increase to the heater unit during contact with the work, to override the rapid temperature drop occurring at the time of transfer.

Figure 11 is a close-up of the transfer head—crude but operational.

In Fig. 12 the operator is "peeling" the teflon support film from a transferred pattern. Note that two resistor pellets have been simultaneously soldered in this sample.

Initial soldering was accomplished using a paste consisting of finely pulverized solder in combination with a neutral flux. The material used is supplied by Eutectic Welding Alloys Corporation and is identified as Eutectic Tinweld III (neutral). It is specifically formulated for automatic soldering of electronic assemblies. It has a tensile strength of 8000 psi and a fusion temperature of 360°F. An undesirable by-product of this substance is a gummy flux residue, which, although chemically inert, requires subsequent cleaning if a quality product is to result.

An alternative flux, produced by Fairmount Chemical Company of Newark, New Jersey, which leaves no residue, has also been evaluated as a possible solution to this problem. For nonporous substrate materials this flux is very attractive. However, epoxy-glass laminates pose potential problems in that excess flux

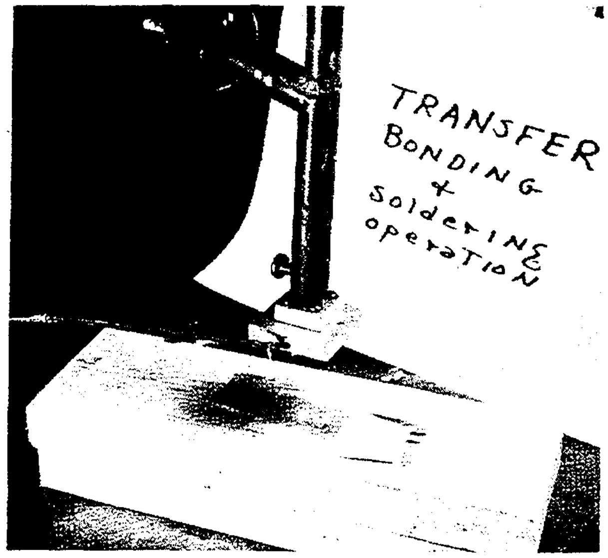


Fig. 11. Transfer head close-up.

material may be wicked into the glass fibers to compromise insulation properties at some later date. Hence, for porous substrate materials, its use is not recommended.

To automate the transfer process we plan to use a sprocket drive, through an appropriate electronic control loop, to accurately register the conductors to the

Fig. 12. Film separation.

substrate contour and to the pellets. The application of a timed heat pulse with compressive force performs three simultaneous functions:

1. The copper/teflon bond is weakened.
2. The "B" stage resin "kicks over," bonding the copper (gold-plated side) to the substrate.
3. The "dot" of solder compound or a thin solder preform disc, provided as an integral part of the pellet component, fuses and "sweats" the conductor tabs to the pellets.

The heat pulse terminates in the pressure head, but pressure is maintained while the assembly is permitted to cool below the solidification temperature of the solder. Heater plattens should be withdrawn from contact with the assembly during the cooling phase.

The soldered substrate is moved forward as the copperless teflon film is accumulated on a take-up reel. Initially it is planned to apply the conductors to only one side of a substrate at a time. The ultimate automation device will apply patterns simultaneously to both surfaces of the substrate. It will also pretest and accept or reject substrates prior to the next sequential process.

In the first assemblies it will be necessary to hand assemble addendum axial lead components and solid state active components. But, as the family of pelletized circuit elements becomes more complete, the end objective is the integrated assembly of all except incompatible components mentioned previously.

It should be obvious that a sequence of different wiring patterns can be etched on any given film strip. This will permit automation of even short runs of modules and will not necessitate a new machine setup for each different wiring configuration.

I should stress again that this technique is not intended to achieve the ultimate in miniaturization. It *is* intended to satisfy the eight objectives defined at the start of this paper—for *analog* circuits.

Problems still exist and require solution before we can say that the process is production-ready. However, we feel that in the very near future most of these will be resolved. Most helpful to the attainment of our goal would be a full family of pelletized components of adequate reliability.

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DISCUSSION

Q. (Greg Mouri, Jet Propulsion Lab., Pasadena, Calif.) Would you mind identifying the adhesive used to bond the copper foil to the teflon? Was the teflon bonderized?

A. The teflon was preprocessed. It is purchased as FEP material, bondable on one side. A hysol resin is used to attach the foil to the bondable surface.

Q. What adhesive was used to bond the copper foil to the pelletized substrate material?

A. We used a dry film adhesive, produced by Circuit Materials Corporation; it is known as X-153. It was applied with a solvent system with the protective paper overlay left in place until just prior to bonding. Hopefully, for a more efficient approach, we would obtain substrate material with the B-stage resin coating preapplied by the laminate manufacturer. We have discussed this problem with Taylor Fibre and others. For small quantity requirements they recommend that we apply the bonding films ourselves. For quantity requirements they would be interested in quoting on the material.

Q. (Stu Hotchkiss, RCA Labs., Princeton, N.J.) The teflon material you describe in your paper as being 10 mils thick with holes punched in it: when you put this in your press and apply heat, how are you able to guarantee a good solder joint without physical contact between your heater block and the solder joint?

A. I would be very cautious right at this moment in saying that I could guarantee a good soldered joint. Hopefully, as work proceeds on this project, we will be able to guarantee the solder joints. We have successfully transferred and performed a solder joint that at least appears to be good. I will honestly say we haven't sectioned a joint and done a microscopic analysis of it—we plan to.

Q. Do you apply any particular pressure?

A. Yes. If I had had a little more time I would have described the transfer machine in greater detail. You may have noticed a loading spring forward on the machine. This is preloaded and adjustable between about 3 and 8 lb of pressure. Something around 5 or 6 lb seems to provide a good bond.

Miniaturization of IF Circuitry

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This paper deals with a project to determine to what extent designs could be simplified and fabrication methodized for miniaturization of analog circuits. The work reported on refers particularly to the miniaturization of a 60-Mc log IF amplifier.

INTRODUCTION

BY FAR THE preponderance of effort and most significant achievements in electronics miniaturization have been in miniaturizing digital circuits. The high-volume repetitive use of digital circuits has made it economically feasible for many engineering firms to subsidize their development. Most of these devices have generally been slow-speed saturating circuits, which are very tolerant of passive-part variations, transistor-parameter variations, and intercoupling capacity and noise effects. Design layout in most cases is reduced to stacking the components, which are generally quite uniform in size, in the optimum volumetric configuration and interconnecting them by simple welded matrices. Thermal problems are straightforward, and electronic or magnetic interaction problems are minimal.

The miniaturization of analog circuits, on the other hand, represents a greater demand on the ingenuity of the product-design engineer and electrical-design engineer; both are mentioned here to emphasize the need for a close-knit team effort when tackling electronics miniaturization in this area. Miniaturization of higher-frequency analog circuits presents too many critical variables to be handled by the "stack them up, interconnect them, and pot them" methods that applied to digital circuits. A disciplined component orientation is absolutely necessary to predict and control stray capacitance. Shielding and grounding become integral parts of the design with close attention to lead configuration and separation of input and output signals. Potting no longer is a simple casting operation; it now requires close attention to uniformity, dielectric constant, thermal characteristics, and the protection of tunable and fragile circuit elements.

MINIATURIZATION OF A LOG IF AMPLIFIER

While many engineers have successfully miniaturized various kinds of analog circuits, few have carried this beyond the model or laboratory-curiosity stage;

for the most part, these efforts were in the realm of feasibility programs with a single prototype or breadboard as their ultimate objective. We at AIL felt that there was a great need for proving the feasibility of manufacturing such equipment on a production-line basis equivalent to that used in the fabrication of digital equipment. We set out to determine, therefore, to what extent designs could be simplified and fabrication methodized for miniature analog circuits. With these objectives in mind, we undertook the miniaturization of a 60-Mc log IF amplifier. This particular circuit was chosen for two reasons:

1. Its precise electronic function under severe environmental and reliability requirements presented all the problems of analog circuits in their most critical form.
2. It had already been packaged in printed circuit form in what is considered to be an extremely compact and highly advanced design; this printed circuit operational aerospace amplifier could serve as a basis for comparison and evaluation of results.

A log IF amplifier is a device capable of instantaneously reducing a large input dynamic range to a small output range that is the logarithm of the input on a pulse-to-pulse basis without limiting, clipping, or distortion. A typical input range of 60 db (or 1,000,000-to-1) is reduced to an output range of 10 db (or 10-to-1) with an accuracy, in this case, of $\pm\frac{1}{2}$ db referred to the input. Thus the amplitude of the output signal is an accurate measure of the received input power.

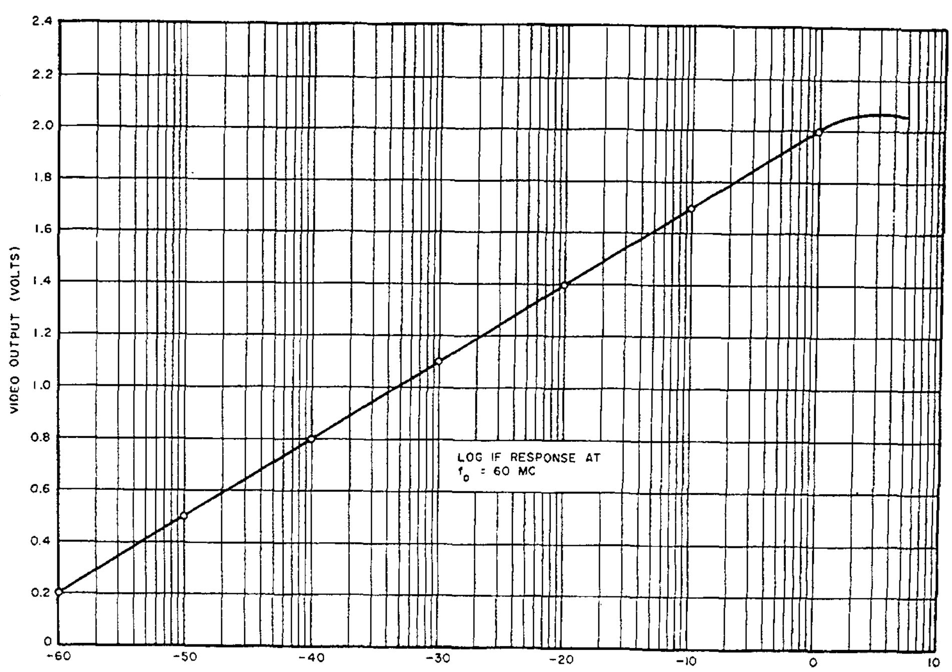

Fig. 1. Input–output curve of 60-Mc log IF amplifier.

Figure 1 is a characteristic curve of RF input (dbm) *vs* video output (volts) for this particular amplifier. Log IF amplifiers are commonly used on long-range radars, ECM systems, and electronic reconnaissance systems.

To justify miniaturizing this printed circuit amplifier and to ensure its immediate usefulness in aerospace systems, it was decided that the miniaturized amplifier must meet the following seven requirements:

1. It must be miniaturized by at least one order of magnitude.
2. It must meet all the operational requirements that its printed circuit counterpart has met.
3. It must be capable of reliable operation in aerospace environments currently being explored.
4. It must be effectively shielded against electromagnetic radiations and radio noise.
5. It must have maximum ease of maintenance and minimum disposable-subassembly cost.
6. It must be made only of circuit components that are reliability-approved.
7. Its components must be interconnected only by a reliability-approved method.

ELECTRICAL MINIATURIZATION

The initial step in any miniaturization effort is to take a long, hard look at the electrical design with an eye toward electrical simplification. In this particular case, considerable reduction in the number of parts was achieved through the use of a higher-gain transistor, which permitted the three-coil, two-variable-capacitor tank circuit to be reduced to a circuit consisting of one tapped coil and one variable capacitor. Further reductions were made by reducing the required supply-voltage by one-half, thereby reducing the ratings required of the components as well as their sizes. This also yielded a 60% power reduction—always a desirable goal in dense packaging. Figure 2 is a schematic diagram of the simplified and miniaturized 60-Mc log IF amplifier.

After this initial simplification and freezing of the successfully breadboarded design, the team effort began with a modularization of the amplifier. Careful examination indicated that the ideal approach would be to modularize the nine identical IF amplification stages and the one video-output stage. With the design problem reduced to that of designing and making only two different kinds of stage modules, future economies would be realized in the reduced number of design drawings, the quantity production of identical modules, the ease of testing and maintenance, and low-cost spares requirements. Modularization was in strict accordance with the electrical design requirements, provided each stage was individually and effectively shielded.

SELECTION OF COMPONENTS AND METHODS

Selection of the smallest *reliable* circuit components available required extensive investigation of the electronic components market. Careful consideration

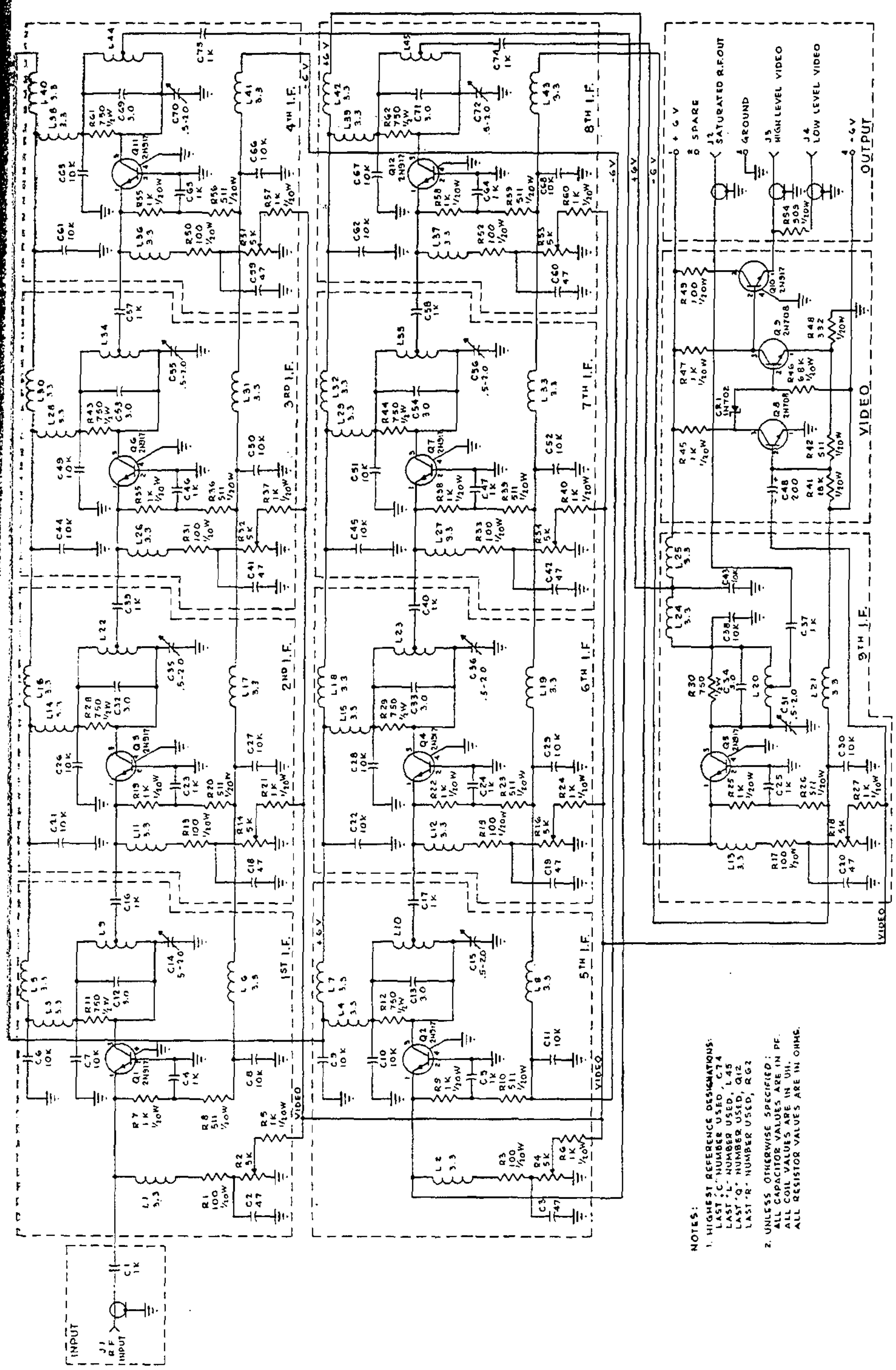

Fig. 2. Simplified and miniaturized 60-Mc log IF amplifier, schematic diagram.

had to be given component size, form factor, lead material, lead configuration, and availability; where substantiating reliability data did not exist, environmental and life tests had to be performed on large sample lots.

Preliminary massing of the selected components indicated that a three-dimensional, high-density packaging technique would have to be used if miniaturization of an order of magnitude was to be attained. Extreme variations in component sizes and configurations precluded the use of two-dimensional printed circuit or deposited circuit methods. Further, whatever, interconnection method was used would have to maintain the three-dimensional volumetric efficiency. Resistance-welding accomplished this and offered the following additional advantages:

1. Connections could be made close to where the leads emerge from the bodies of the components without risk of thermal damage. This permitted minimum lead lengths, which are not only desirable for size reduction but essential in higher-frequency electrical design.
2. The simplicity of a skeletal interconnection system reduced the potting problem of obtaining a uniform, predictable dielectric.
3. The elimination of variable amounts of conductive connection material —such as solder or conductive epoxy resins—controls stray capacitance, reduces weight, and minimizes the chances of accidental shorts.
4. The high strength of welded interconnections permits necessary tuning and testing prior to the potting operation with less danger of circuit damage.

DESIGN CONCEPT

Based on modularization of the IF stages into a three-dimensional, high-density welded package, design standards were set to ensure that the amplifier would meet the seven requirements that were established earlier. These standards were, in brief:

1. All external connections to a module would be located on only one side of the module to facilitate ease of assembly and replacement.
2. Power connections would be symmetrically located to permit linear bussing of all modules.
3. The input and output connections would be physically separated by ground.
4. The tunable elements would be located opposite the connection surface of the module to permit adjustment of the assembled amplifier.
5. A module would be completely potted in a minimum-weight potting compound to protect it in an aerospace environment.
6. Each module would be effectively shielded from the others in the finished amplifier.
7. The interconnected modules would be completely encased in a metal container and securely grounded to that container.

These standards were rigidly adhered to and resulted in the amplifier shown in Fig. 3 alongside its printed circuit counterpart. The amplifier consists of 12 equal-size modules: an RF input module, which doubles as a cover and RF seal for the amplifier case; nine identical IF stages; a video module; and an output module, which also serves as the power manifold for the amplifier. The individual modules are interconnected by welded ribbons, and the assembly slides into a thin-walled rectangular aluminum tube. Each module is securely fastened and grounded to the tube by two opposing screws.

DESIGN OF THE INDIVIDUAL STAGES

The design of a single-IF-stage module was generated in accordance with AIL standards for welded electronic assemblies to further ensure the reliability and reproducibility of the final design. These standards are a definitive set of documents that govern the design, drafting, fabrication, and inspection of welded electronic assemblies.

By simply stacking the selected components required to make up the IF stage, a module size of $1 \times 1 \times \frac{3}{8}$ in. was determined to be feasible, which would permit an order of magnitude miniaturization to be realized. To obtain the required interstage shielding and to provide a good ground plane that could be duplicated exactly from module to module, the stage would be constructed on a 1-in.-square nickel sheet. (Nickel was chosen for its desirable welding characteristics.)

Component orientation was determined by means of ten-times-scale drawings,

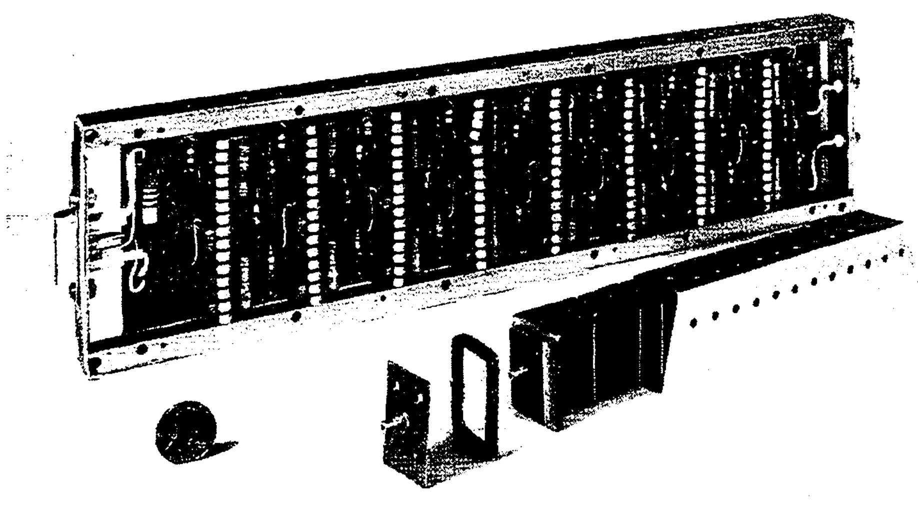

Fig. 3. Simplified and miniaturized 60-Mc log IF amplifier and its printed circuit counterpart (in background).

paper cutouts, and dummy mock-ups placed within the desired size configuration and oriented to obtain minimum interconnection-lead lengths and the most direct, centralized ground returns. This board work was closely coordinated with the construction of full-scale working prototypes, which were used to work out the shielding, grounding, and other electrical problems.

Figure 4 shows the IF-stage module prior to potting. Note how the transistor collector and emitter are shielded from each other, with the transistor base grounded to the shield. This is an excellent example of what is meant by making the shield an integral part of the design rather than an afterthought or fix. Tuning is accomplished with the tunable piston-type capacitor, and logging is accomplished with the potentiometer. The components are positioned so that they can be adjusted from the top of the module, opposite the connection lead side. The module is mounted and grounded through two self-locking nuts welded to tabs on opposite edges of the base plate. Another point of interest is the great saving in space accomplished by winding the tank-circuit coil directly on the body of the tank-circuit damping resistor.

Fabrication of these stages was accomplished by first fastening the larger components to the nickel base plate and then, using their leads as terminals or binding posts, the smaller components were welded in place. A more detailed description of this procedure will appear in the drafting-techniques section of this paper.

The video-stage module was designed in a similar manner. This was a far simpler undertaking; however, because the circuit was less critical, there were fewer components, and there were no tunable elements.

The input- and output-stage modules were designed with two purposes in mind:

1. To provide a good mounting for the input and output coaxial connectors

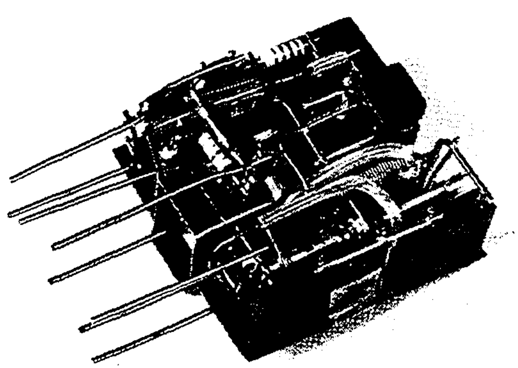

Fig. 4. IF stage module before potting (shown about 2× size).

and the power connectors and bring their leads to the interconnection side of the modules.

2. To provide end seals for the modular assembly when the amplifier is inserted in the metal-tube case. These seals must not only be mechanically sound; they must also serve as RF seals.

The design of the input- and output-stage modules is quite straightforward and need not be discussed further.

DRAFTING TECHNIQUES

The assembled IF stage module (Fig. 4) is quite a complex package to present in standard, multiview layout drawings. To realize the paramount goal of this effort, therefore, and enable draftsmen to draw it and production-line personnel to build it, a simpler graphical representation had to be devised. This was accomplished by preparing a series of stage-assembly drawings of a module; each drawing showed the complete module assembly in light phantom lines and, superimposed in heavy lines, the components to be assembled at a certain stage. A ten-times-scale series of drawings was prepared for each module, the number of drawings in a series being dependent on the complexity of the module. In each case, the drawings were prepared in the following manner:

1. A four-view orthographic-projection layout drawing of the complete, unencapsulated module was prepared, showing all the parts drawn in phantom lines.
2. Reproducible prints (sepias) were made from the layout drawing.
3. For each module-assembly process step, those parts that were to be mounted, assembled, etc., were heavy-lined onto one of the sepia prints. In this manner, a series of drawings was generated which gives a step-by-step presentation of the assembly and welding processes. These drawings were then numbered consecutively "Operation 1," "Operation 2," etc.
4. On each of the stage-assembly drawings the following information was added:

   a. Location and orientation of components.
   b. Location, size, and composition of all interconnecting ribbons and wires.
   c. Locations of all welds.
   d. Identification of all components by part number and description.

From the sepias, smaller transparencies were made and were used, along with weld schedules, as instruction sheets for the welders and assemblers who fabricated the modules.

A full-scale photoreduction of the first stage-assembly drawing, showing only the larger components on the base plate, was used to fabricate a stencil for accurately marking base plates. The larger components were then permanently fastened to the base plate with an epoxy-resin adhesive.

With the larger components in place, the fabrication follows along in orderly steps as shown on the transparent overlays. We found this method to be quite efficient, and the fabrication could be done by semiskilled labor with a minimum amount of training.

POTTING THE INDIVIDUAL STAGES

The potting or encapsulation of higher-frequency circuits—such as our amplifier—presents many new problems and considerations over and above those encountered in potting digital modules. The aerospace environment requirements alone demanded that the amplifier be solid-potted for shock, vibration, and thermal dissipation. In addition, the application necessitated that the potting material be light in weight and have a low moisture-absorption and sublimation rate.

The electrical considerations required that the potting material have a low and extremely uniform dielectric constant if stray capacitance was to be kept to a predictable minimum. In addition, the nature of the components themselves required that the potting material have a low curing temperature and shrinkage rate to avoid damage to the component while the potting material is curing.

The sum total of the requirements dictated that an epoxy-resin compound be used. Fillers would have to be added to the potting material to overcome the objectionable curing stresses and high dielectric constant, while the uniformity of the dielectric would have to be controlled in the mold design and molding technique.

The only filler which can appreciably reduce an encapsulant's dielectric constant is air. This can be done fairly uniformly by using microballoons—tiny,

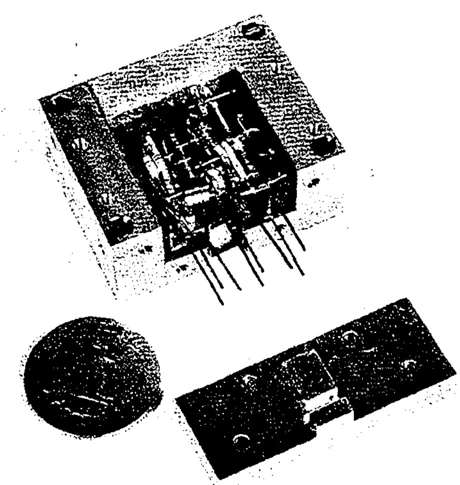

Fig. 5. Potting mold and header with cores and IF stage module in place.

hollow ceramic spheres produced by the Emerson-Cummings Co. The microballoon-filled epoxy resin fulfills all the requirements, but its high viscosity makes it difficult to mold. This and the uniformity problem, however, were resolved through good mold design and the development of appropriate molding techniques.

The mold consists of a polished-aluminum frame into which the module is placed with its nickel base plate at the bottom. Stainless steel cores, coated with a release agent, are threaded through the frame and into the mounting nuts. Teflon tubes are pushed over the tunable-element adjustment screws. The external connecting leads are held in a removable, polished-aluminum header. Figure 5 shows this mold with its cores and header and with an IF-stage module in place.

The only preparation the module receives is a thin precoating of the glass piston capacitor with silastic rubber to protect this fragile component from the curing stresses. The potting compound is then very thoroughly mixed, preheated, and injected under pressure through the open top of the preheated mold. The overflow is machined off after curing.

The potting operation did cause a shift in the center frequency of the IF stage. Because of the uniform dielectric constant achieved, this was corrected simply by a change in the fixed tank capacitor.

MODULE INTERCONNECTION

The most important requirement for the technique to be used in interconnecting the various modules composing the amplifier was that it be highly reliable in accordance with AIL standards for aerospace equipment. In addition, we sought a technique that would eliminate interference between input and output lines, permit straightline bussing to as great an extent as possible, simplify module assembly and replacement, ease testing by providing accessibility to necessary test points, and require the least possible space.

The interconnection method chosen for the 60-Mc log IF amplifier was point-to-point welded nickel ribbon. More precisely, all connections between modules were made to straight nickel pins brought out on a single, common side. These pins were interconnected by means of nickel ribbon welded from module to module. The pins were located on the module face in an array that facilitated straightline, one-piece, nickel-ribbon bussing. In addition, RF input and output pins were recessed and separated by a grounded shield on each and every module. This permitted the signal buss to be recessed and shielded from the other busses and eliminated undesirable interstage coupling.

This welding technique provides high strength and reliability and meets the requirements outlined previously. The entire interconnection area protrudes only $\frac{1}{8}$ in. beyond the module face. The pins were made extra long so that a module can be removed from the amplifier for testing and reinstalled in the amplifier a number of times before the leads become too short requiring that the module be discarded. To replace a suspected faulty module in the amplifier, the pins and busses are merely clipped and a new module put in its place and rewelded to the interconnection busses.

After the amplifier receives its final electrical check, the interconnection busses are potted with a Dow-Corning dielectric (Gel) which affords environmental protection while still permitting future testing repairs.

TESTING

The amplifier is tested on both a module-by-module basis and on a complete-assembly basis. Each module receives a simple functional test prior to encapsulation to ensure that it has been welded properly and that all components are operating. A special test jig has been constructed for testing the unpotted modules to reduce the danger of damage caused by excessive handling.

After potting, the individual stage module undergoes an intensive testing, tuning, and alignment procedure. Again, a special jig, which simulates the module's position (mechanically and electrically) in the finished amplifier, is used. The modules are checked for gain, saturation level, center frequency, and bandwidth.

After making the interconnections and checking for proper continuity, the entire amplifier is slid into its case and all final assembly operations are performed, including alignment of the amplifier. The alignment procedure for an amplifier of this type is usually quite complex but, because each stage has been prealigned, our procedure is much simpler; it consists merely of adjusting the logging potentiometers in a prescribed order as the input is increased in discrete steps. This task is rather tedious but by no means complicated. Curves of logging characteristics both on and off the center frequency are plotted for every amplifier tested. These curves are kept as a permanent record of an amplifier's operation.

CONCLUSION

The successful order-of-magnitude miniaturization of the operational log IF amplifier has proven the practicability of miniaturizing higher-frequency analog circuits. This particular amplifier is already slated for use in both an aircraft-borne and in a satellite-borne system. What is most important is that the amplifier exists, not as a laboratory curiosity, but as a completely designed and methodized product that can be produced in quantity when needed.

DISCUSSION

Q. (Ed Shower, Sperry Semiconductor, Norwalk, Conn.) I would like to congratulate the author on his emphasis on one point that seems to have been missed by several of the other authors. And that is the insistence that a redesign of an electrical circuit be rather carefully looked into before one embarks on miniaturization. I am sure that as we go into more sophisticated circuitry that this matter will become even more important.

Q. (General Electric Co., Syracuse, N.Y.) I was quite interested in your method of documenting not only the build-up of the module but a subsequent manufacturing sequence. Is this done in conjunction with your manufacturing engineering organization or is it solely the responsibility of engineering?

A. No. At AIL we have a separate manufacturing engineering department and they had a representative working with our miniaturization group to help us document and methodize our designs.

Q. (Greg Mouri, Jet Propulsion Lab., Pasadena, Calif.) You talk quite a bit about the potting compound. I was curious to know whose manufacturer's brand name you used and what the code number was.

A. Our final choice in potting compound was Emerson-Cummings 10-90, which is an epoxy compound filled with ceramic microballoons.

Q. Which catalyst did you use—9 or 11?

A. We used catalyst 9 for precoating the module and catalyst 11 for final potting.

Q. Is the gel you use for potting your interconnection Dow material?

A. Yes, Dow Corning Silguard 182.

Q. (Martin Camen, Bendix Corp., Teterboro, N.J.) Have you done any hard-vacuum testing of Emerson-Cummings Stycast 10-90?

A. Yes, we checked the sublimation rate and found it to be within our requirements.

Q. (Don Schnorr, RCA, Camden, N.J.) In potting of this assembly did you run into any trouble with lead breakage when the potting compound started curing?

A. Yes. Very early in the program all the prototypes were put together with soldered interconnections, and we did have some breaks.

Q. (Frank Jarvis, Raytheon Co., Bedford, Mass.) Had you considered the possibility of using the small epoxy preformed cases to get you around the requirement for actually putting the preassembled module in a metal mold and pouring it full of the potting compound? It might save you some cost and complexity.

A. Yes. Early in the program we were actually planning, for weight savings, to go to a foamed stage using a metal can; but at 60 Mc your ground returns are very critical, and we found that when we stacked the stages up, the different points of contact, which always vary, changed the ground returns and gave us many feedback and instability problems. We are using a small preformed epoxy case on our thin-film amplifier, and this is working out very well.

Q. (Carl McKann, Motorola, Phoenix, Ariz.) In the build-up of the individual modules what did you use as a structural plate, or base plate?

A. The base plate was a nickel sheet about 15 mils thick.

Q. There is no printed circuit board or anything of this sort involved?

A. No. Again at 60 Mc we want to keep our interconnections isolated, shielded, and as short as possible. We found that by using the larger components as terminals we eliminated additional circuitry and gained the freedom of the third dimension to attain our design requirements.

The IMP—A New Concept in Miniature Module Construction*

R. D. ZIMMER AND F. A. KOTTWITZ

Cedar Rapids Division, Collins Radio Company, Cedar Rapids, Iowa

This paper describes the Welded Miniature Module Development of the Interim Miniaturization Program, Collins Radio Company, Cedar Rapids, Iowa. The program was undertaken as a necessary step to bridge the time gap between current conventional electronic packaging techniques and microminiaturization methods such as integrated thin-film circuits, planar diffused circuits, and molecular circuits.

INTRODUCTION

ANY INTERIM packaging method must meet an impressive list of specifications, but also must utilize fabrication processes and parts that are in existence or that can be developed in a relatively short time period. Process and product specifications established for this development include the following:

1. High reliability
2. Low finished product cost
3. Use existing welding or soldering fabrication techniques
4. Low process and module development cost
5. Use commercially available parts and processes
6. Module size comparable with other component oriented packaging, such as Signal Corps micromodule
7. Provide geometry with high multiple unit packaging efficiency
8. Provide for adequate heat removal
9. Provide leads adaptable to a simple connector or point-to-point interconnection
10. Provide structural integrity to meet airborne, missile, and field environmental requirements

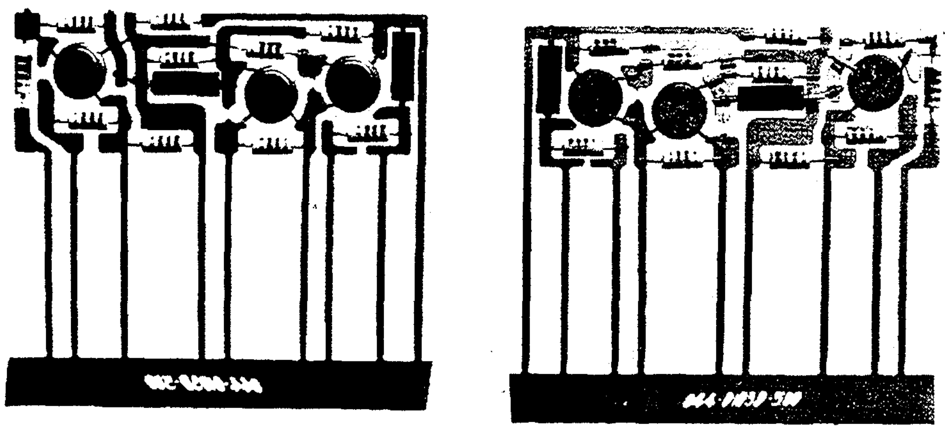

Fig. 1. A typical unencapsulated IMP module.

Based on these criteria, the process developed for producing IMP modules consists of the following primary steps:

1. Prepare schematic drawing of module
2. Establish parts selection and design layout
3. Prepare expanded scale artwork
4. Make photoreduced negative, and step and repeat
5. Produce etched circuitry
6. Gold-plate circuitry
7. Weld component parts onto circuitry
8. Perform pre-encapsulation tests
9. Encapsulate
10. Make final test on module

A typical unencapsulated IMP module produced by this process is shown in Fig. 1. The process is illustrated in Fig. 2.

DESCRIPTION

Consideration that this was a packaging process development and not a parts development program indicated that any increase in reliability would have to be attained in such areas as new designs, novel fabrication techniques, or environmental protection and not through any increase in parts reliability. This is not to imply restriction to the use of high-reliability parts in any way. Just the converse is true, as this process will allow the use of any selection designed to fulfill the desired performance requirements. Increase in reliability is attained by eliminating one complete set of interconnections and an additional inherent increase in reliability is gained through the use of welding and encapsulating.

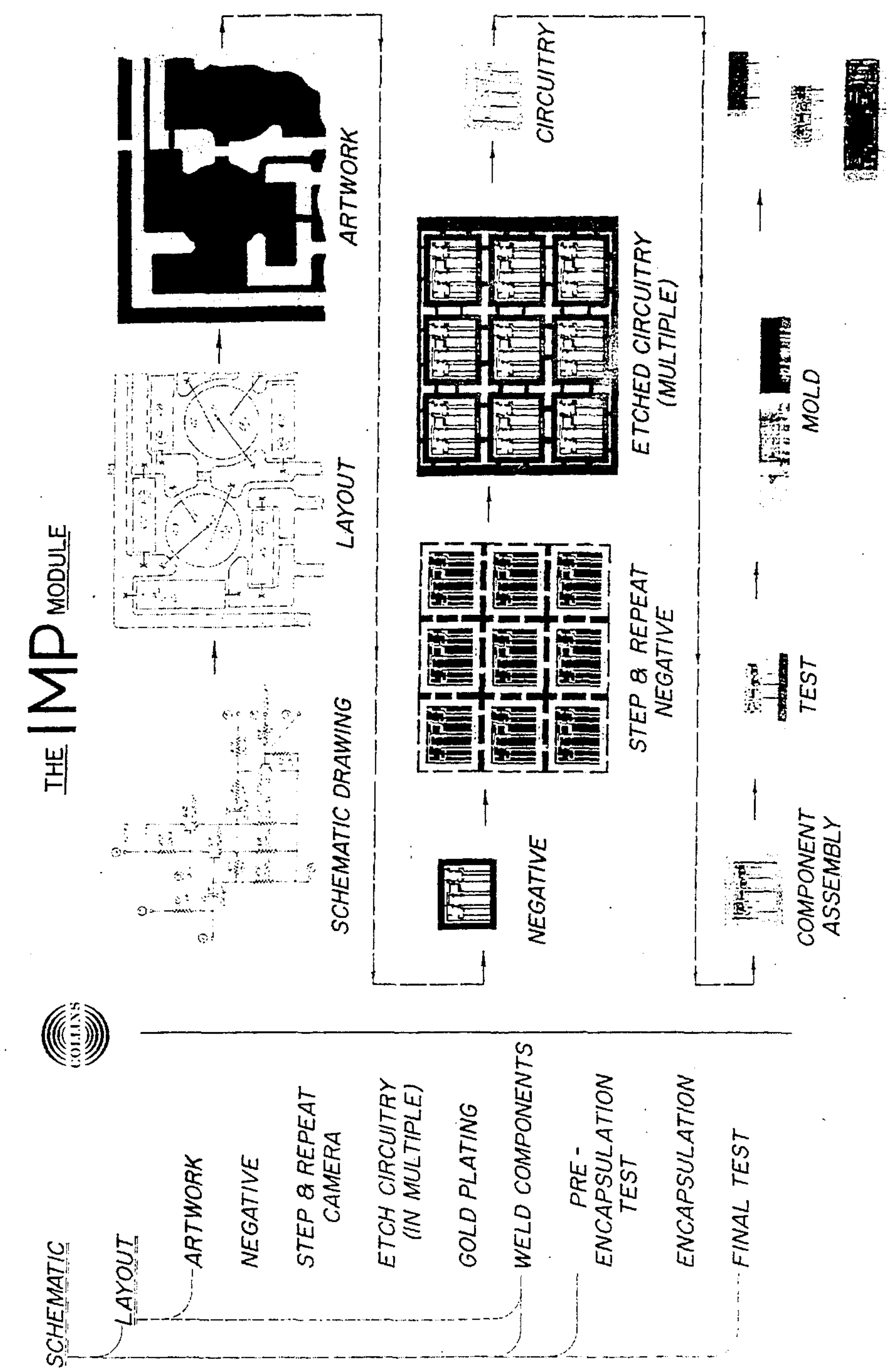

Fig. 2. IMP process flow chart.

Low cost is realized in all respects, except for the basic cost of parts. Parts cost can be as high as 90% of the total cost. Reduction in parts costs was not within the scope of this program. It is now evident that the greatest remaining possibility for cost reduction exists with the parts, and further, this cost will be affected considerably by various microminiaturized integrated circuitry developments.

The following is a comparison of the combined parts and fabrication costs for a typical application where both of the packaging methods mentioned use the same electronic parts:

Unit	Method	Cost
F-105 steering	Present packaging	$1019.33
Computer and flight		
director subsystem	IMP	$680.00

Inasmuch as the costs are primarily the costs of parts, it is evident that quantity, availability, and other purchasing factors are very important.

Fabrication costs are expectedly quite low as there are very little tooling and capital equipment costs to be included. The process was developed to make use of existing etched circuit facilities, assembly benches, personnel, etc. The only addition necessary was the miniature spot-welding equipment. These welders are quite effective, in that they require little bench space and operator training is not difficult. The cost of such a welder including the power supply is usually under $2000.

The primary items of cost in this development were: evaluation of the various packaging methods proposed, selection and evaluation of base and encapsulation materials, evaluation of various welding equipments, and the establishment of weld schedules, environmental tests, and reliability tests.

The final packaging configuration is adapted easily to nearly all electronic parts from conventional to miniature, and lends itself as a method of mounting integrated circuits into a single package of modular geometry. This has resulted in densities up to 100 times conventional packaging at the subassembly level, with consistent improvement of ten times. Studies have shown that further improvement in packaging density can be attained by careful attention to electrical design and selection of miniaturized parts.

The mounting of the final module divides naturally into two types. These are: First—plug-in units with a newly developed miniature female socket having interconnections to the socket made either point-to-point or interconnected with an etched circuit board. Second—modules that are clamped (bolted) rigidly to a chassis with the interconnecting pins accessible for point-to-point connections between modules. A module of the second type is shown in Fig. 3.

A basic two-dimensional configuration was selected because of its inherent advantages in assembly, heat removal, and high packing density when stacked. The two-dimensional module has ideal accessibility for assembly and lends itself

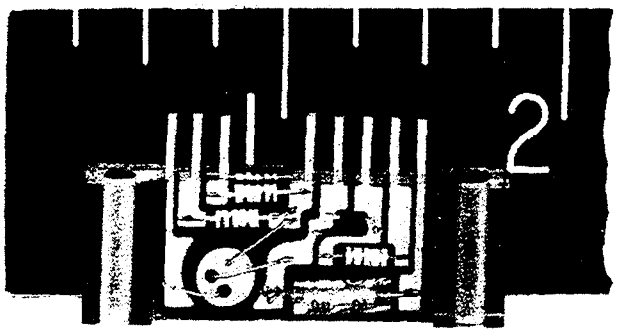

Fig. 3. IMP module for bolt-type mounting.

naturally to assembly automation. The modules can either be stacked together or spaced as necessary for thermal considerations. The two-dimensional module provides maximum surface area for heat dissipation by radiation as well as by conduction and convection.

The small encapsulated modules are very effective against extremes in operating environments, and with a minimum of consideration can be packaged into a system which is similarly effective.

Note should be made here that even though the module is encapsulated, there is no automatic guarantee that all parts are hermetically sealed. For maximum reliability, sealing should be done at the part level. Encapsulation functions primarily to provide structural integrity.

The final configuration meets all the dimensional requirements of the new revision of Naval Air Development Center, Specification NAVAIRDEVCEN EZ 5-13A, dated 1 May 1962 except 3.4.2.1.5: "Leads shall be of circular cross section with a nominal diameter of 0.017 in." Even though this can be accomplished, it does not lend itself very conveniently for use in the IMP module.

DISCUSSION

Q. (Jay Block, Aerospace Group, Hughes Aircraft Co., Culver City, Calif.) Would you elaborate further on the jigging process used for holding the parts in place during the welding operation?

A. The jigging fixture is formed by drawing a vacuum on a sheet of thermoplastic, which is heated in place over a completed assembly. The vacuum holds the thermoplastic sheet to the shape of the assembly, which is then allowed to cool. The cooled sheet is removed and holes are punched through the points through which welds are to be made. The assembly process using this fixture required that the part leads be precut to length and the base plate and parts placed into the fixture and then fed into the welding electrodes for the welding process. This is just one of the techniques; others are presently being contemplated.

Q. (Leonard Marks, General Dynamics/Astronautics, San Diego, Calif.) What type of material and what thickness of material is used to make the interconnections?

A. The interconnecting material, the width of this material, and its thickness are selected on the basis of many considerations. Three of these considerations are (1) heat sink capability, (2) weldability, and (3) compatibility with the etching process available. The base material that was found to be most useful for our particular process was 10-mil beryllium copper, gold flashed.

Q. Have you attempted to use nickel to obtain better weldability characteristics and also to eliminate the gold flash?

A. Nickel has been used quite satisfactorily for welding and it also makes a good heat sink. It is probably easier to weld than beryllium copper although the beryllium copper has not presented any serious welding problem. The welding equipment that we are currently using is adequate to weld about any combination of materials that has been considered. The reason that we did not use nickel in our final product was primarily due to the lack of mechanical strength. This becomes most important in the pins or leadouts from the module which mates with a connector. The beryllium copper leads will stand considerable abuse and do not bend out of line easily. Another consideration, of course, is the desirability of being able to solder to the leadouts for point-to-point wiring. This might possibly be done with a solderable nickel.

Q. (Al Ryan, Hughes Aircraft Co., Los Angeles, Calif.) Your expanded scale artwork is produced from the laminated cut mylar. At Hughes we use a pressure-sensitive tape on a mylar base in order to prepare the artwork. Do you prefer one method over the other?

A. I do not prefer one method over the other. The process that was available for use on this project happened to use the laminated cut mylar. This process certainly provided satisfactory artwork. It was not within the scope of this project to study methods of producing the required artwork.

Q. (Dean Joachim, Univac, St. Paul, Minn.) The slide which showed your connector assembly did not show the connection side. Is this connector designed for taper pins or wire wrap?

A. The connector in its present form, as furnished by Cannon Electric Company, is designed for a typical solder connection. I am sure that with some modification this could be adapted to almost any type of connection that might be desired. I might elaborate a little further on this connector. It is designed to accept a rectangular-shaped pin, 10–20 mils thick and about 20–40 mils in width. It is just possible that this connector would accept a round pin, however this has not been verified.

Q. (Joe Walentine, RCA Labs., Princeton, N.J.) I have heard talk about encapsulating epoxy materials creating excessive stresses on welded or soldered joints and I would be interested to know if you have used any epoxy which does not shrink excessively during the hardening process.

A. Probably the simplest solution to this problem is to use an epoxy encapsulant which does not set up so rigid that it causes excessive stresses. This is accomplished by a variety of compounded epoxies, some of them containing plasticizers. I would expect this information would be available from the various epoxy vendors. The basic requirement is to provide an encapsulating material that has enough flexibility at the required temperature extremes to prevent internal stresses and, at the same time, provide adequate mechanical support for the module.

Q. (Herbert Morgan, Sylvania Electric, Mountain View, Calif.) It appears that some of the interconnections are islands. How are these islands supported while the parts are being assembled?

A. In the finished module that was displayed there are at least two islands. The number of islands depends to some extent on the experience and capability of the layout draftsman. These islands are held in by base-plate material throughout the assembly operation and are severed prior to testing and encapsulating. It is possible that in some cases this material would not be needed and the part leads could be joined directly.

Q. (Roy Malarik, Lear Siegler, Grand Rapids, Mich.) I saw no provision in the finished module for its support in the next assembly. How do you plan to support it in the final unit?

A. The module, as is, can be stacked with a clamp over a group of modules, say 10 or 15 or whatever might be desired. There are many approaches such as allowing for, and using, a through bolt down the center or along the sides of whatever might be required for dynamic stability. These modules can also be stacked with aluminum shims between the modules, which are grounded to the chassis to provide heat sink capability. There seem to be so many possibilities and so much flexibility in the use of these modules that we have not attempted to set up any standards. The only exception that seems advisable is to adhere to the $\frac{1}{10}$-in. grid. This seems to be an accepted standard throughout the industry.

Q. (Joe Ritter, Electronic Modules, Timonium, Md.) This is not a question, but I would like to caution the use of plasticizers and flexibilizers in epoxy. These additives do not always accomplish a long-term desired result. I think that before anyone actually uses these additives that they had better do some life testing. You may find that over an extended period of time you will have as hard an epoxy as if you did not use them.

High-Frequency Analog Circuitry

STEPHEN A. SLENKER

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This paper discusses three basic approaches to a simple and inexpensive, yet flexible, method for construction of analog circuitry. The unique features of cordwood geometry, pill components and multiple wafer components will be presented.

INTRODUCTION

THERE ARE many unique problems encountered in packaging analog high-frequency circuitry in the frequency range of 30 to 70 Mc. Since analog circuitry is by nature subject to continual redesign, it is highly desirable to have a somewhat flexible method of construction that is simple and inexpensive. Three basic approaches have been utilized to achieve this end: (1) the use of miniature standard components in a cordwood geometry; (2) the use of "pill" components; and (3) the use of multiple wafer components. The unique features of each packaging scheme will be discussed.

HIGH-FREQUENCY ANALOG CIRCUITS CONSTRUCTED IN THE CORDWOOD GEOMETRY

The cordwood geometry offers the greatest circuit flexibility in the high-frequency range. Standard components of any size can be accommodated and tunable components are easily utilized, in contrast to smaller packaging schemes where it is extremely difficult to use tunable components. Since most tunable components are physically large, the overall package is inherently large. Cordwood construction has sharp right-angle bends in the interconnection leads. The sharp bends cause radiation, thereby lowering circuit efficiency. Also, the general geometry yields longer lead lengths than other packaging schemes. The longer leads result in signal losses and in unwanted inductive coupling between signal paths.

Ground loops are much more troublesome in cordwood geometries than in the other construction methods owing to the frequent carrying of grounds between printed circuit boards. This problem can be reduced somewhat when a double printed circuit board is used, where one side is used as a ground plane, as shown in Fig. 1. The main problem encountered in this construction technique has been

Fig. 1. A double-sided printed board with one side used as shielding.

the difficulty of replacing faulty components in the center of the assembly. Another common problem in military applications is the temperature stabilization of the critical circuits to meet the broad temperature range required by military specifications.

Temperature Stabilization of Cordwood Modules

A method of controlling the temperature drift in cordwood packages has been investigated. This method involves the use of a Westinghouse PTC thermistor, Type 802-1, which was used uncased and was cut to a 0.2-in.-diameter circle using an S. S. White Industrial "Airbrasive" Unit (see Fig. 2). A typical characteristic of power dissipated *vs* temperature for this device after being cut to the desired shape is shown in Fig. 3. The thermistor was inserted into a cordwood module in the vicinity of the components which were the most temperature-sensitive. Thermally conductive epoxy was used to encapsulate the subassembly of thermistor and temperature-sensitive components. The remainder of the cordwood package was encapsulated in thermally insulating (standard) epoxy or cross-linked polyethylene.

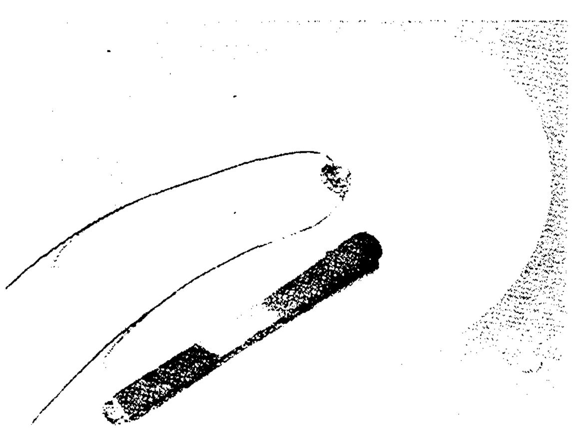

Fig. 2. Modified PTC thermistor.

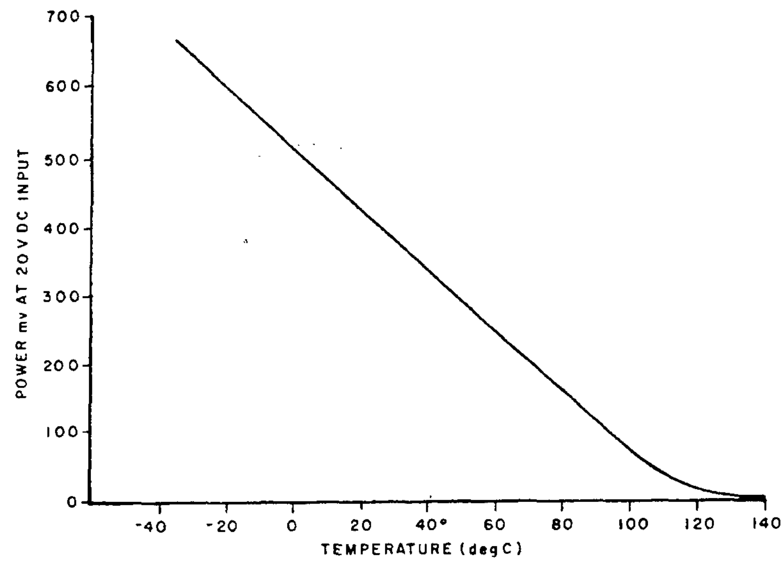

Fig. 3. Power dissipation *vs* temperature for an uncased Westinghouse PTC Thermistor Model 802-1.

The initial experimental package contained a transistor with and without the thermistor voltage applied. The β of the transistor *vs* temperature is shown in Fig. 4. It is seen that the thermistor maintains the transistor constant to within $\pm 5°C$ when the external ambient temperature is changed from $-55°$ to $+125°C$. The electrical properties of the thermally conducting epoxy indicate that it is satisfactory for most high-frequency applications.

There is a disadvantage in using this system as a temperature control. It should be realized that the device stabilizes the temperature by maintaining it at the upper level of the temperature range. Since there is a smaller thermal safety factor employed in the design, the system is prone to failures caused by transient overloads.

It is interesting to note that the thermistor does not substantially decrease the power-handling capability of nearby transistors because the thermistor "cuts off," that is, it dissipates a negligible amount of power when the ambient temperature is high. Heat leakage is *required* to maintain a constant temperature and to prevent thermal runaway. In small signal applications, the amount of heat generated is usually small enough so that the leakage of the inherent geometry is sufficient. Higher-power applications may require greater heat leakage. The heat leakage is determined by the thermal resistance of the particular geometry under consideration and may be calculated using an Ohm's law analogy[1].

It should be observed that as the heat leakage is increased (or the thermal resistance decreased), the regulation quality of the thermistor is reduced. The best thermally conductive epoxy generally has a thermal conductivity 20 times the thermally nonconductive types. This ratio of thermal conductivities limits the

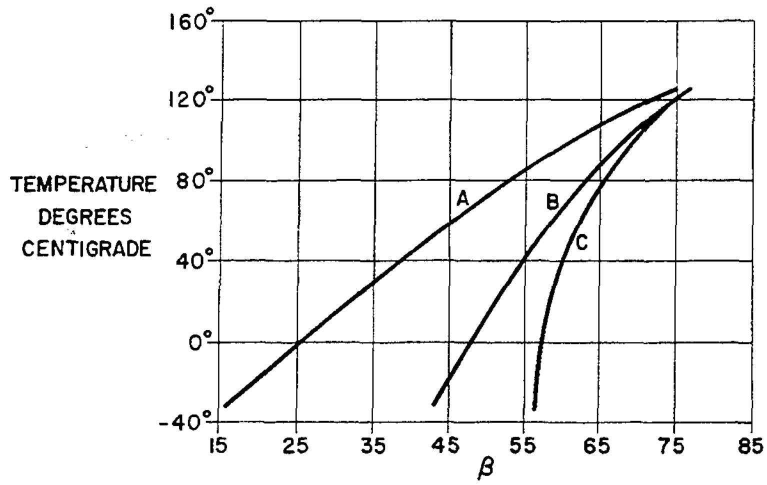

Fig. 4. Temperature cycle of an FM 917 transistor showing the variation in β with temperature. (a) Transistor unencapsulated, (b) Transistor unencapsulated with a thermistor attached by thermally conductive epoxy, (c) Transistor encapsulated in thermally insulating epoxy with a thermistor attached by thermally conductive epoxy.

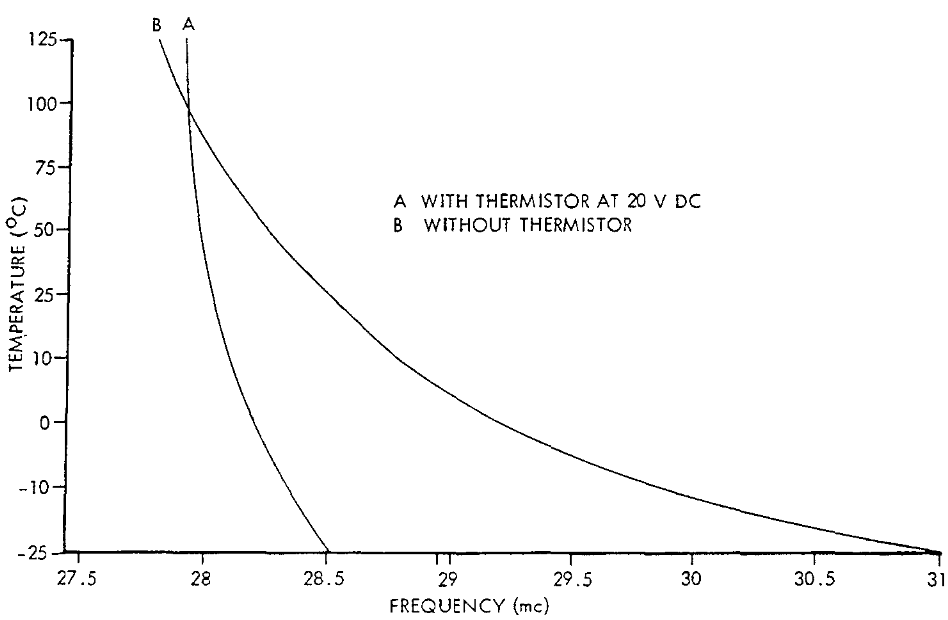

Fig. 5. Center frequency *vs* temperature with and without thermistor compensation.

extent to which the thermal resistance can be reduced without suffering loss of regulation from temperature gradients within the thermally conductive epoxy.

As a practical example of the regulating qualities obtained, a thermistor was used in an IF amplifier with various combinations of epoxies. Temperature effects are shown in Figs. 5 and 6. With the thermistor connected, the gain was 10 db less than with the thermistor disconnected. The decrease in gain is assumed to be caused by higher I_{c0} which occurs at the elevated temperature. Greater frequency and amplitude stabilities were obtained with the thermistor connected.

General Construction Techniques Used in the Cordwood Geometry

In order to show the application of the general techniques utilized in the cordwood geometry, an entire IF strip was constructed using the cordwood approach as shown in Fig. 7. The coil form used in the cordwood was Type CTC-LS11, which was modified to reduce the overall height. The split ring, terminal board, and rubber spacer were discarded and the case was made shorter by 0.036 in. A piece of 0.018-in. flexible printed circuit board with a ring pattern was soldered to the coil form shell. A Formica Type FF89 board containing printed circuit wiring on both sides was used. Transistors of the FM918 and FM708 variety in the TO-46 microbloc case were mounted back to back. Standard $\frac{1}{4}$-w Ohmite or Allen Bradley resistors were used in this model as this resistor type was readily available, inexpensive, and appeared to have adequate temperature stability and mechanical strength.

The interconnections were made between modules by using a double-sided

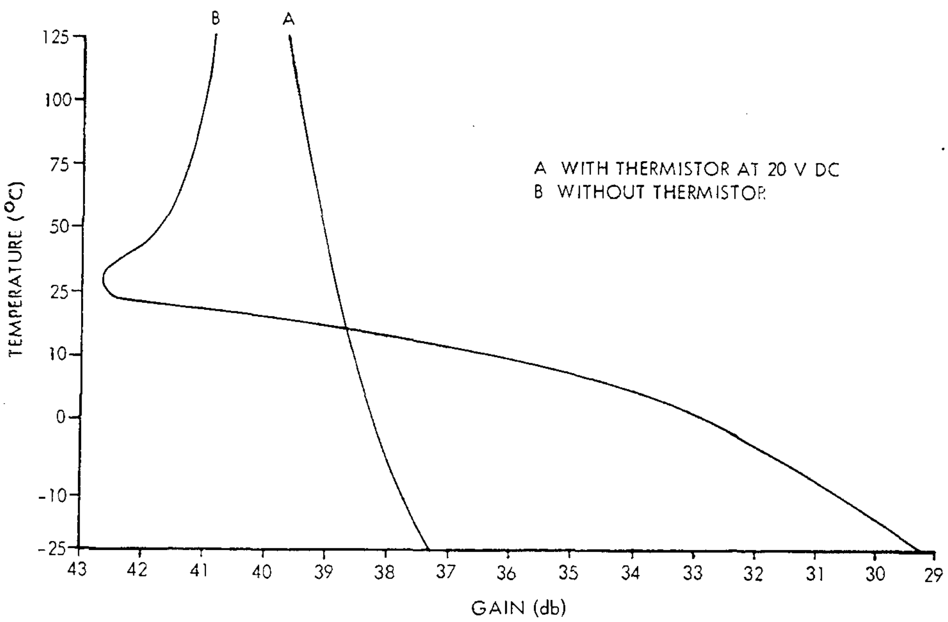

Fig. 6. Gain *vs* temperature with and without thermistor compensation.

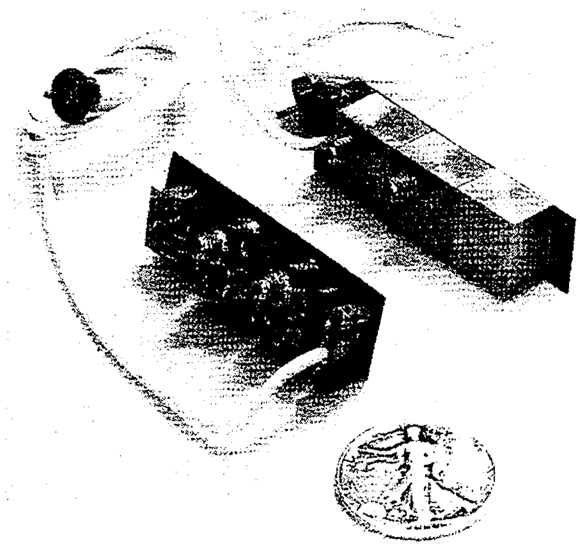

Fig. 7. Cordwood construction of an IF strip.

printed circuit board. The outer side of the interconnecting board was used as a shield. Each amplifier module was individually shielded by plating copper onto the plastic. The diode in the base-biasing circuit was used for temperature compensation. From the graphs Figs. 5 and 6, it can be seen that the characteristics changed with temperature but that the change was quite linear. By using a temperature-compensated capacitor, a desired characteristic such as the center frequency could be held quite constant.

Circuit Considerations in the Cordwood Geometry

Microminiature circuits should be solely designed from a size and reliability standpoint rather than from any consideration of component cost. (The reasoning used here is that component cost is so changeable, depending on quantities used, that any cost assumptions made at the initial design stage will probably be completely erroneous by the time the product reaches the production stage.) Based on this philosophy, the utilization of as many transistors as possible in place of bulkier passive elements is appropriate since transistors are generally the smallest components used in electronic assemblies. If modularized construction is to be used, scrupulous examination of the schematic should be undertaken in order to determine the best place to break the circuit into modular blocks.

An example of the simplifications that were made on a circuit is shown in Fig. 8. A standard geometry amplifier was first considered. The circuit simplifications were made and then the circuit was broken into modules and assembled as shown. A standard IF amplifier design which contains 2 tunable inductors, 10 capacitors, 2 transistors, and 8 resistors is shown in Fig. 8a. This circuit had a

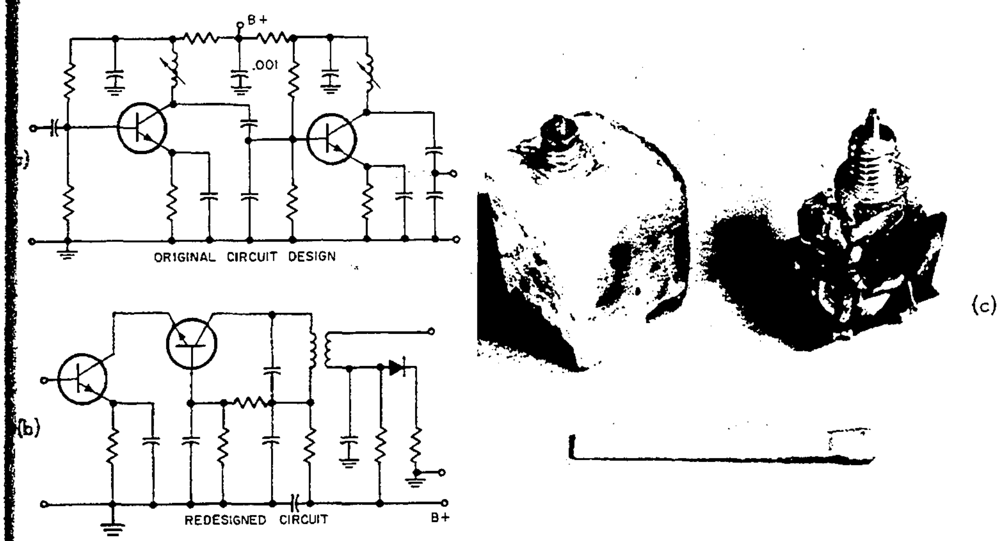

Fig. 8. Circuit considerations for an IF amplifier module.

gain of 45 db at 30 Mc. Figure 8b shows a cascode circuit containing 1 tunable inductor, 6 capacitors, 2 transistors, 6 resistors and 1 diode. This circuit has a 27% parts saving over the circuit of Fig. 8a and has a 42-db gain at room temperature. The modified circuit was then packaged as shown in Fig. 8c.

It was then noted that by rearranging the biasing network, a saving of space could be made within the package. The input biasing network could be placed at either the front or back, so the biasing network was installed at the front end. The resulting circuit and package are shown in Fig. 9. This package uses only two terminal boards and yields a 25% volume saving over the earlier design of Fig. 8c.

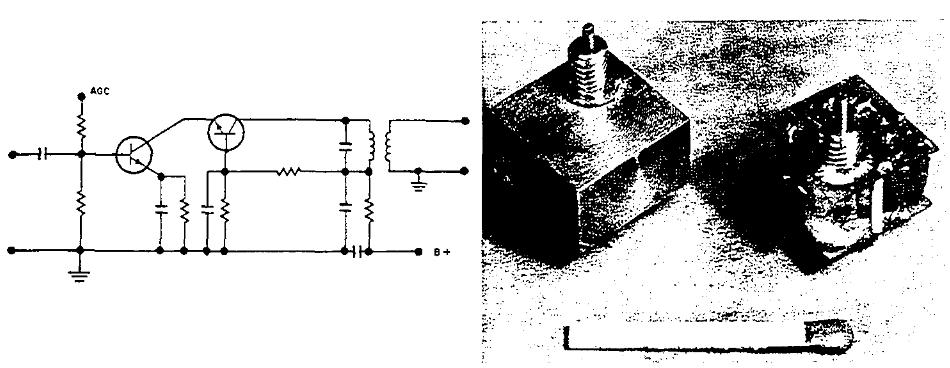

Fig. 9. Circuit modifications given an IF amplifier module.

HIGH-FREQUENCY CIRCUITRY USING THE PILL GEOMETRY

The "pill" type of component may be used to construct high-frequency circuits with fewer ground loop problems than are encountered in the cordwood approach. The pill concept has the disadvantage that most conventional tuned components cannot be used. The pill construction uses a uniform circuit geometry so that few problems in detuning are caused by variations in the interconnection geometry. Assembly in the pill substrate generally involves application of soldered interconnections. Repairs can be made by unsoldering and lifting the interconnection pattern. Because pill components are smaller than the components used in cordwood packages, the pill geometry usually yields a packaging density between two or three times the packaging density of cordwood components.

There are a few tunable components that are readily adaptable to the pill geometry. There are some screwdriver adjustable potentiometers that have approximately the same thickness as the pill components, and they could be inserted into the substrate without serious packaging problems. Tunable capacitors could easily be developed to operate in the pill-substrate geometry since capacitors are inherently flat as a result of the parallel-plate construction. No tunable capacitors thin enough to be utilized in the pill geometry are commercially

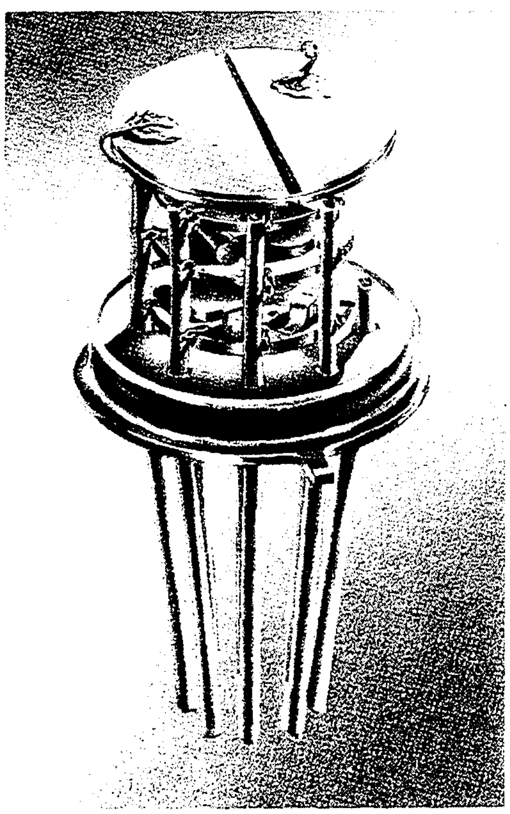

Fig. 10. A method of construction used on an IF amplifier.

available, however. The most difficult pill component to develop would be a tunable inductor. Inductors are generally bulkier than other components.

PARTIALLY INTEGRATED CIRCUITS

The smallest packaging scheme presently available for high-frequency analog circuitry uses modified standard components in conjunction with integrated or thin-film resistor–capacitor networks. The general packaging geometry consists of parallel planes containing the components, which are interconnected along the edges by various techniques. The interconnection method involves ultrasonic welding of short conductors to contacts on a thin-film component board and standard electric welding of the short conductors to riser wires inside a TO-5 transistor case. Transistors are mounted on ceramic or glass substrates. An IF amplifier fabricated using these general techniques is illustrated in Fig. 10. Thermal compression bonding is used to mount and interconnect individual components to the boards.

By using ultrasonic and standard welding techniques to make all of the interconnections between boards within the package, it is possible to prevent the interconnections from becoming disconnected by the application of heat when the assembly is soldered into a system.

SPECIALIZED COMPONENT DESIGN FOR MICROMINIATURIZED ASSEMBLIES

Particular attention should be given to the construction of the components in order to achieve minimal size packages. A series of specialized components has been developed to be used in this assembly. It should be noted that many of the

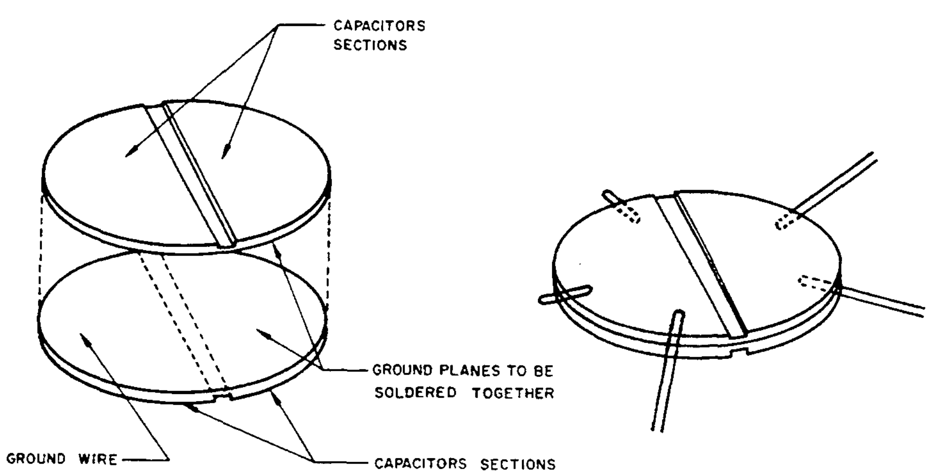

Fig. 11. Special construction of bypass capacitor.

components in such a system must be made by the assembler for prototype circuit designs. In the assembly of Fig. 11, the coils and capacitors were fabricated by the author and the transistors and diodes were purchased.

A unique construction was used to obtain bypass capacitors in an extremely small space. The method of construction is illustrated in Fig. 11. Circular bypass capacitors were made by first abrasive-cutting the silver-plated ceramic disks to the required diameter. Then a line was abraded on one side of each disk to separate the conductor plate into equal semicircles. Two semicircular bypass capacitors were then stacked back to back. This scheme permits a reasonably stable, bulkier dielectric-constant ceramic to be used in the assembly, and yields four 0.003-μf capacitors in a compact geometry. In production, these capacitors would be made by pressing out circular pieces in the green state, rather than abrasive-cutting to a circular shape. Smaller capacitors than illustrated could be constructed by using a material with a higher dielectric constant, but these materials have been too unstable with temperature to be suitable for most circuit applications.

Extremely small inductors have been constructed for use in these assemblies. Photographs of inductors are shown in Fig. 12. Both ferrite and powdered iron

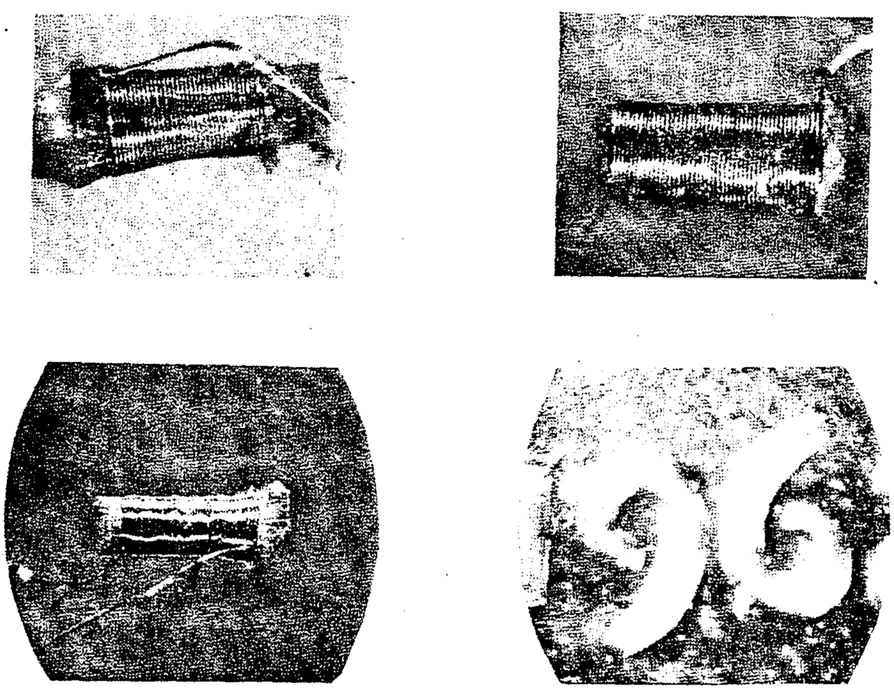

Fig. 12. Microphotographs of small coils used in the microassemblies. All microphotographs are taken at the same magnification (approximately 80×). Upper Left: 2.2 μh, Q = 55 at 30 Mc., length = 0.0535 in., width = 0.0285 in. Upper Right: 2.64 μh, Q = 55 at 30 Mc., length = 0.0688 in., width = 0.0340 in. Lower Left: 2.4 μh, Q = 44 at 30 Mc., length = 0.0591 in., width = 0.0186 in. Lower Right: The date on a penny used as a size reference.

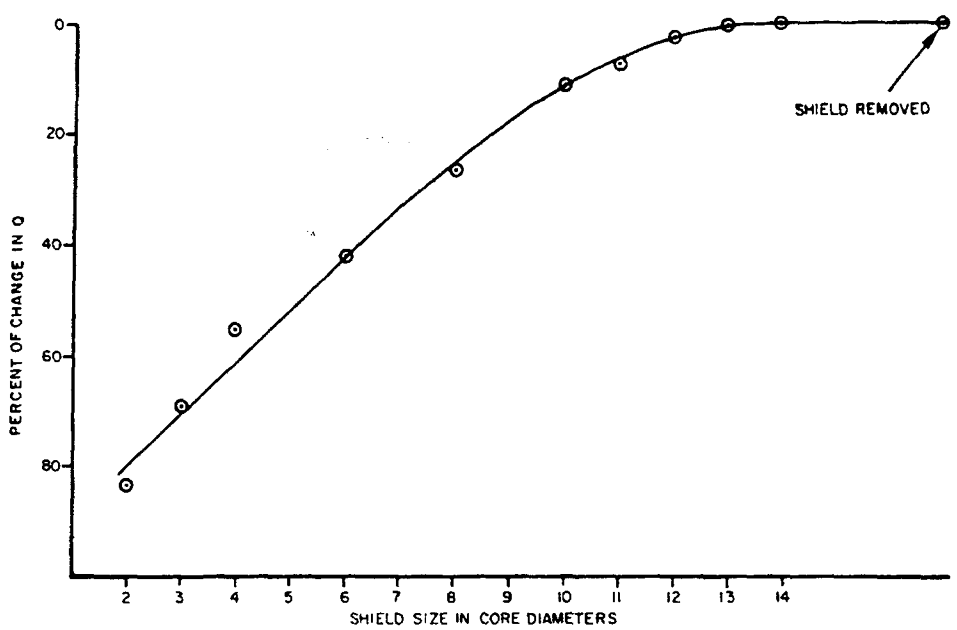

Fig. 13. Coil Q *vs* shielding for a coil with shielding placed around the coil.

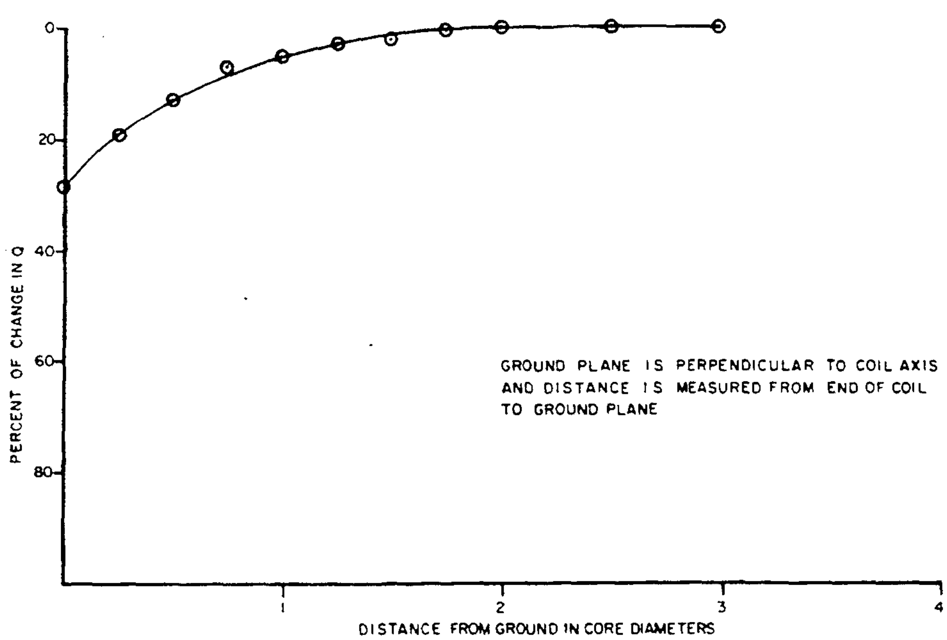

Fig. 14. Coil Q *vs* shielding for a coil with shielding placed at an end of the coil.

core materials have been tested and fairly similar results have been obtained. The ferrites exhibit slightly higher Q but have slightly less temperature stability. Reasonably high Q's are readily realized in this package even though the size is extremely small. Measurements indicate that coil Q is not substantially reduced by reducing the coil size, if the proper core materials are used and the geometry and physical construction are carefully considered. The maximum unsaturated power-handling capacity is reduced when a coil is made smaller. An interesting observation is that shielding around coils does not always reduce the Q by a substantial amount. Plots of Q *vs* nonmagnetic shielding distance for a 5-Mc coil with a Q of 400 are shown in Figs. 13 and 14. These curves show that it is advantageous to use coils of extremely small diameter. Although nonmagnetic shielding greatly affects the Q when placed around the coil to act as a shorted turn, little effect is observed when the coil has shielding material only at its ends. Therefore it is seen that assemblies within a shielded case should contain coils whose geometry is a tiny cylinder of small diameter rather than a thin-film spiral of large diameter.

CONCLUSIONS

Three of the basic approaches to microminiaturizing high-frequency analog circuitry have been reviewed in an attempt to inspire further interest in the field of electronic circuitry which requires the utmost flexibility in assembly techniques to provide inexpensive modification procedures. It is hoped that this youngest branch of microelectronics soon will be abundant with suitable hardware and assembly techniques so that the analog circuit designer can accomplish the same space, weight, and power savings that are realized in the digital area.

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DISCUSSION

Q. (Martin Camen, Bendix Corporation, Teterboro, N.J.) Could you elaborate on the case where you have only the transistor in the encapsulation?

A. Figure 4 shows a curve for the transistor unencapsulated with no thermistor attached. If the transistor were running at a low power level and the heat leakage were appreciable, the curve would be the same as Fig. 4a providing the measurements were taken after waiting for a longer time to reach thermal equilibrium. If the encapsulant provides appreciable thermal insulation, then the curve will be shifted to the right an amount depending on the thermal leakage characteristics of the material and the heat injected by the transistor, the increased β indicating a higher junction temperature.

Q. Are most beta changes for an uncompensated transistor in the low-temperature range?

A. The beta change is almost linear with temperature when you have no thermistor attached.

Q. If you look at curve *C*, near the top of the curve why does a slight change in temperature give a change in β?

A. In this region the thermistor is operating at the knee of its characteristic curve and is beginning to become ineffective.

Q. Have you contemplated using a thermoelectric cooler?

A. It does not have any built-in temperature monitor. It would need an additional device like a thermocouple to measure temperature. A cooler would dissipate more power and would generate much more heat than a thermistor and this heat would need to be removed from the package.

Q. (Dean Bailey, Motorola Semiconductor, Phoenix, Ariz.) We have also been doing some work in the TO-5 and we found that the toroid is a better approach because of less leakage flux which would change X_L. Have you looked into the toroid?

A. There are two reasons why I did not use the toroid. One is that the toroids generally occupy about two or three times the volume, and the other is the poorer temperature stability which is a result of no air gap.

Q. Well, our toroids are powdered iron, which has very stable permeability because of its distributed air gap and we can obtain in a TO-5 can on a $\frac{1}{8}$-in. toroid up to 2 μh at a *Q* of about 50.

A. The toroids you have built are about four times the volume of the coils in my paper.

Q. (Gene Thoenstet, Sperry Phoenix, Phoenix, Ariz.) I am afraid I missed the name of the maker of that coil. Did you make it and if so, how?

A. Yes, I made the coil. The coil forms were cut down to the required diameter by grinding, and the core material was held in a jig similar to a hand drill, which was mounted to a bench.

Q. (Harry Baker, Philco, Palo Alto, Calif.) The gentleman's comment on the toroid was fine as far as the *Q*, but I think he would have a little difficulty tuning it. I believe your circuit showed inductive tuning.

A. The circuit has inductive tuning in the potted module, but not in the transistor can version. Tuning in the smaller version can be accomplished by trimming the ceramic capacitor across the coil with an SS White "airbrasive" unit.

The Design of a Chemically Milled and Adhesive-Bonded Airborne Indicator Unit

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This paper describes the use of chemical milling and adhesive bonding for construction of strong, lightweight, reliable chassis for airborne electronics equipment. Also included is an addendum describing results of vibration tests carried out for airborne equipment.

INTRODUCTION

AMONG THE requirements for airborne electronic equipment are small size and light weight, which must be achieved without sacrifice of reliability, serviceability, and high performance. Engineers of the Airborne Operation have for some time been studying the use of chemical milling and adhesive bonding for construction of strong, lightweight, reliable chassis as a major step in realizing these qualities.

The opportunity to prove the feasibility of these techniques came during a reliability improvement study on the B-58 search radar. It was decided that the indicator unit should be completely repackaged and certain circuit modifications made for improved reliability and performance.

Increased reliability and performance of electronic equipment may be accomplished by circuit redesign, by component re-evaluation and selection, by repackaging, or by combinations of these procedures. The electrical improvements, however, rely heavily on the packaging configuration and its strength and reliability. Only the mechanical redesign of the indicator is covered in this paper.

The original indicator is shown in Fig. 1. It is made up of a magnesium-base casting and a sheet stock framework assembled by riveting and welding. The unsymmetrical shape with the cutout portion at the rear was dictated by its location in the aircraft. The unit is supported in the bomb/navigation rack by eight Dzus fasteners on the front panel and two locating pins on the rear casting adjacent to the three main electrical connectors. The loading characteristic is similar to a beam supported at the ends, and requires the chassis structural members to carry the maximum bending forces (taking place approximately in the center of the unit). This odd shape and method of mounting provide a good proving ground for the new design techniques.

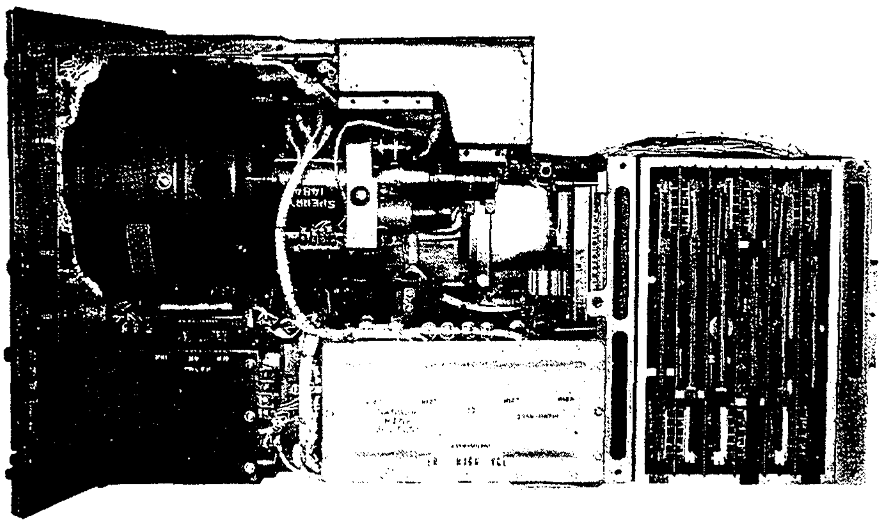


Fig. 1. B-58 search radar indicator.

In addition to the inherent obstacles of shape and method of mounting improved mechanical features included the paramount design considerations of ease of manufacture and maintainability. Therefore, modular packaging was used wherever adaptable to the design configuration. The CRT assembly, cable harness, transformers and printed circuit panel assemblies were designed as separate entities to allow individual fabrication, assembly, and electrical and mechanical checkout on the production floor, while requiring only the physical installation of these units in the Indicator chassis. It is not difficult to appreciate the savings in time and money which can be realized by this procedure.

A wooden mock-up of the Indicator chassis was constructed during the embryonic design stage in order to evaluate all design ideas. The major subassemblies and parts were provided with pegs and dowels to be readily removable in order to point out the design features (see Figs. 2 and 3). This mock-up became invaluable in relating the electronic subassemblies, chemical-milled parts, bonded areas, and general construction and maintenance features.

The design program was by no means a single-company effort, as Raytheon was ably assisted by three other concerns. The chemically-milled chassis parts were made by the Chemical Contour Corporation of Gardena, California. Assistance in the selection, method of application, and supply of the proper adhesive was given by the Bloomingdale Rubber Company of Aberdeen, Maryland. The machining of parts, fabrication of the bonding fixtures, and actual bonding of the chassis were done by the Ludwig Honold Manufacturing Company of Philadelphia (Folcroft), Pennsylvania. The cooperation, coordination, and performance of these companies in building the first unit was extremely satisfactory.

Both chemical-milling and adhesive-bonding techniques are relatively new;

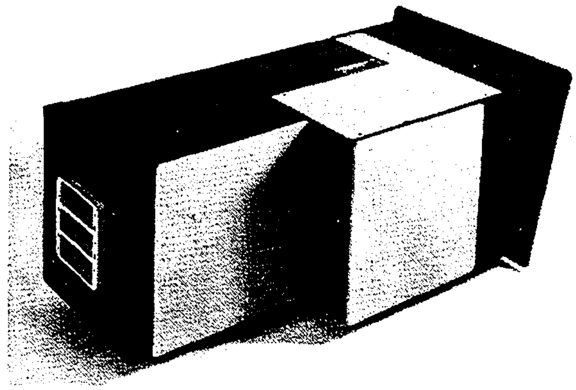


Fig. 2. Mock-up, redesigned indicator.

questions naturally rise at this time: "Why use these types of metal working and fastening instead of other methods of fabrication?" "Can we substantiate their use in this design application?" In order to meet the requirements of a high strength-to-weight ratio and density of packaging as it exists in the Indicator, it was necessary that the design use as many flat, thin sections as possible, attached without excessive hardware and without highly stressed areas. Chemically-milled components bonded by an adhesive fulfill these requirements to a satisfactory degree.

CHEMICAL MILLING

Chemical milling is the controlled removal of metal by a chemical etching action. By selective masking of metal areas not to be milled, extremely close tolerances and intricate contours are attained, and complete repeatability between parts is realized. Clearances for electrical components such as relays and capacitors can be custom-designed for optimum strength-to-weight ratio. Strengthened attaching bosses can be provided as integral pads on complex shapes. Reinforcing ribs of any

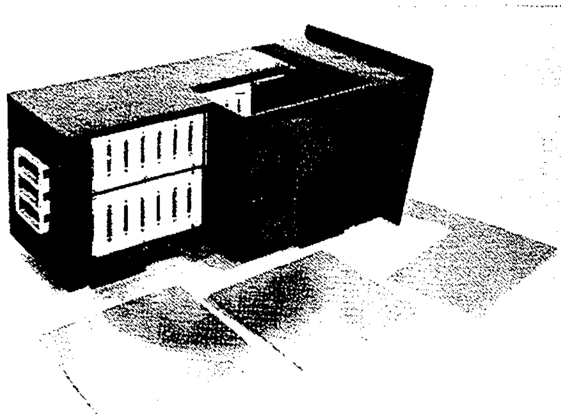


Fig. 3. Mock-up, covers removed.

shape or pattern can be produced to add strength to large, thin-section areas, and to prevent resonance and "oil-canning" conditions. See Figs. 4 and 5 for examples of chemically-milled chassis parts.

The basic steps in chemical milling are:

a. The part to be milled is first carefully cleaned, and then completely coated with a rubber-type masking material.
b. The coated part is cured in a special oven.
c. The pattern to be milled is cut away from the rubber in accordance with a contoured fiberglass template. The scribing and preparation of the coated part is performed by skilled technicians.
d. The prepared parts are carefully inspected prior to etching.
e. The milling (etching) is done in large tanks of etching fluid with precisely controlled time and temperature to obtain the required depth of etch. Materials such as aluminum, steel, magnesium, stainless steel, and beryllium copper are some examples of metals successfully chemical-milled to date. Etching depths up to 0.500 in. with a tolerance of ± 0.010 in. are standard practice. Fillet and minimum corner radii are usually equal to the depth of cut. A surface finish of 125 μin. rms is standard.
f. The parts are cleaned chemically; all rubber coating material is removed, leaving a bright clean finish.
g. The parts are given final inspection.
h. Finally a protective finish or coating is applied to parts that have surface treatment requirements.

After chemical milling, the parts for the indicator chassis were machined for special radii, holes, and surfaces. All mating surfaces of components to be adhesive-bonded were machined to a 63-μin. rms finish, and to ensure a chemically clean surface, these parts were fluoride anodized after machining. After anodizing, the parts were immersed in a protective oil bath (Texaco Rust Proof #564, or equivalent)

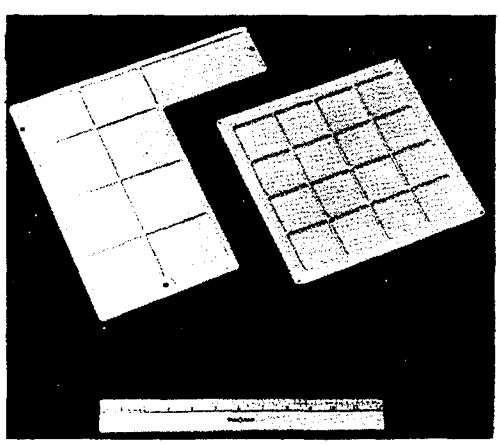


Fig. 4. Cover plates, chemically milled.

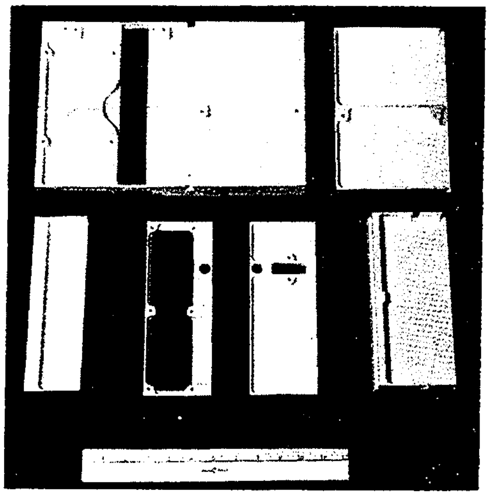


Fig. 5. Chassis members, chemically milled.

for protection during shipment. At Ludwig Honold Manufacturing Company, the parts were given a thorough dimensional checkout. Following inspection, the parts were degreased, and placed in protective polyethylene bags for storage until ready for the adhesive bonding operations. Just prior to each bonding operation, the parts involved were stripped in a hot solution of 10% chronic acid and given a final surface protective treatment of DOW #9—MIL-M-1371 Type IV. After this treatment, all parts were handled with clean white cotton gloves and covered with protective aluminum foil to prevent further contamination.

ADHESIVE BONDING

Today, rapid progress is being made in efforts to improve the performance and reliability of existing materials and, through research and development programs, to design entirely new ones. Structural adhesives are an outstanding example of new materials developed for many uses in recent years. The airframe industry was among the first to bring structural adhesives into the limelight. From the development of the B-58 weapon system appeared a new concept of airframe construction as radical in departure as the replacement of the wood and fabric aircraft by the all-metal monocoque structure. In the B-58 development program, many different designs of airframe skin coverings were evaluated, including riveted-sheet-stringer construction and adhesive-bonded structures. Only the bonded construction produced the desired properties of improved aerodynamic smoothness, high structural efficiency and simplicity of design. As a result, the B-58 bomber is 95% adhesive-bonded.

In any new process, the vital factor is the ability to reproduce parts consistently with required standards and specifications. The adhesive-bonding process is not infallible, as variables can creep in (improper surface cleaning, inferior prime metal finish, adhesive aging, and variations in cure, thickness, and method of application). However, the advantages of adhesive bonding outweigh its disadvantages.

Adhesive bonding was selected for the following reasons:

a. It has high strength-to-weight ratio. A general weight reduction can result from elimination of fastening hardware.
b. Loads are uniformly distributed throughout the bonded area. There are no high-stress concentrations as found in conventional welded or brazed sections because residual stresses are eliminated in the curing phase of the bonding operation.
c. Bonded parts show good damping qualities; the adhesive is elastic enough to absorb stresses induced by flexing and by differences in coefficient of expansion.
d. Adhesives can join dissimilar metals and materials, and in some cases are the only satisfactory method. Adhesives also provide electrical insulation and minimize galvanic corrosion.
e. The adhesive acts as a sealant. This is highly desirable since the Indicator's heat transfer uses air in a closed-loop cooling path.
f. The adhesive provides a good surface for organic coatings.
g. The process does not embrittle magnesium or aluminum, or tend to warp steel as in the case of welding.
h. Critical alignment of joined parts is easier.
i. Highly skilled technicians are not required to perform the bonding operation, resulting in lower labor costs.
j. Cost savings can be realized by bonding large areas in a relatively short time, by elimination or reduction of the number of fasteners, and by the reduced number of forming and machining operations.

The following disadvantages must be weighed against the advantages:

a. Cleanliness and surface preparation of parts to be joined is critical for strong reliable joints.
b. Heat and pressure are needed to cure the bonded joints, requiring the use of expensive jigs and fixtures.
c. Parts to be bonded must have mated surfaces to ensure strong and reliable bonds.
d. Some adhesives are susceptible to high humidity and extremes in temperatures. The selection of the right type of adhesive for a particular job can require extensive research and experimentation.
e. Adhesive bonding is a relatively new method of joining parts; there are less reliability and performance test data available.
f. Inspection of joints and nondestructive testing is difficult or impossible. It is necessary to rely upon test sample data for each lot of parts being bonded and cured.

Adhesives, in general, have been studied by various groups and individuals within the company for several years. Many reports and papers are available. For this design program, consultations were held with Bloomingdale and Ludwig Honold to discuss the design plans, structural requirements, and specifications which led to the selection of the adhesive being used in the bonding of the Indicator chassis. As a parallel effort, a test program was conducted by Raytheon's Process and Materials Section on bonding of magnesium with various adhesives and surface treatment finishes.

The results of this preliminary investigation revealed that for bonding magnesium parts, the greatest adhesion can be obtained by using parts which have been primary-cleaned in a hot solution of 10% chromic acid with no protective surface treatment applied to the surfaces to be bonded. It is not practical from a production standpoint to follow this procedure because of the short time permissible between the primary cleaning and the application of the adhesive. For practical purposes, Dow 7 (MIL-M-3171 Type III) and Dow 9 (MIL-M-3171 Type IV) are the best surface treatments for good adhesion between bonded surfaces. The Dow 9 treatment was the final choice for the alloys selected (HK-31 wrought magnesium and QE-22-T6 magnesium alloy casting). Following this surface treatment, the parts were rinsed and then heated to 150°F for 15 min prior to adhesive bonding.

Of the adhesive tested, Bloomingdale's unsupported film HT-424, modified phenolic epoxy-type adhesive, was selected as best suited to our application. Other types may yield higher lap shear stress values at room temperatures, but they have lower values than HT-424 between −60° and +260°F, the environmental temperature range of the Indicator.

An unsupported type of film adhesive (0.005 in. thick) was used instead of the supported type because it compresses more readily, thereby compensating for any irregularity in the surfaces to be bonded. It does not soften after its initial cure (350°–359°F) during multiple curing operations. The curing time is 45 min using a pressure of 75 lb on the bonded joints. Type HT-424 has excellent bond strength through a wide temperature range in both processing and end use.

FINAL ASSEMBLY

The assembly, bonding, and final machining of the Indicator chassis were done by Ludwig Honold. Prior to the bonding operation, inserts for screw threads were assembled on some chassis parts which would not be accessible after bonding. The front housing (Fig. 6) and rear-end casting (Fig. 7) were finish machined, all bonding surfaces were carefully checked, and the parts used in each bonding fixture were assembled in place on a dry-run basis to check out the parts, adjacent mating surfaces, bonding fixture, and the adjustment of the proper pressure on the fixture clamps and pressure pads.

Because of the basic layout of the chassis (see Fig. 8) it was necessary to divide the bonding operation into three successive stages. The first stage consisted of the assembly and bonding of the front housing casting, baseplate, and air duct covers (see Figs. 9, 10 and 11). The second stage was the bonding of the center skeleton section to the base plate (see Figs. 12, 13 and 14). The third and final stage assembled the previously bonded subassemblies to the rear-end casting and top plate (see Figs. 15 and 16).

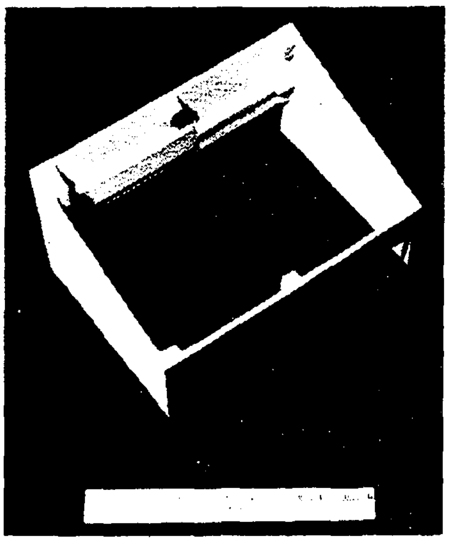


Fig. 6. Front housing casting.

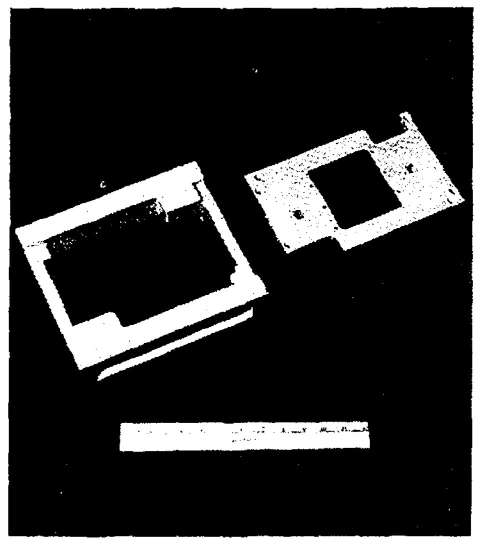


Fig. 7. Rear-end casting.

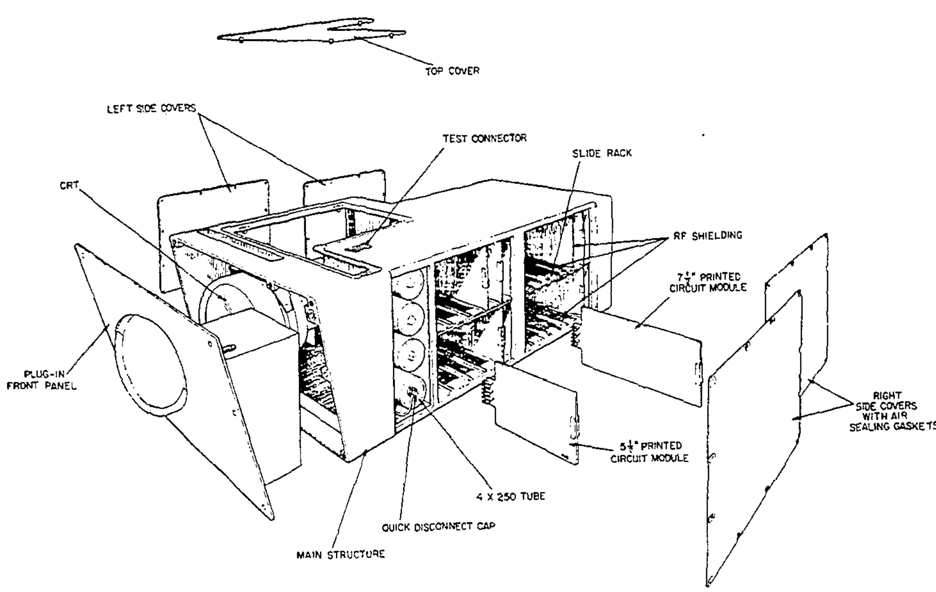


Fig. 8. Indicator—artists concept.

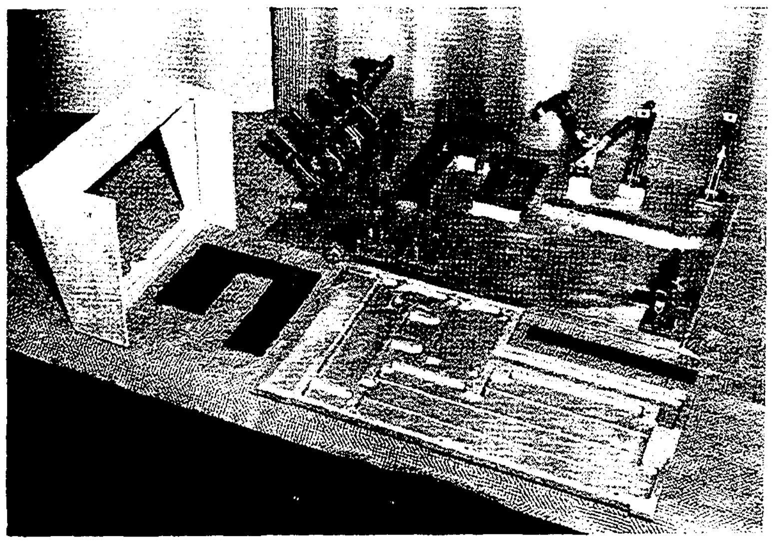


Fig. 9. First-stage jig and parts.

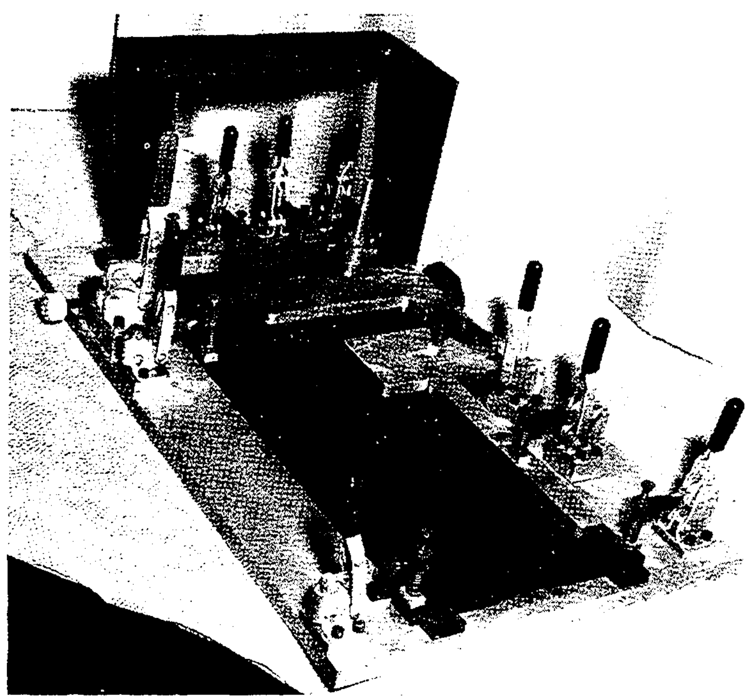


Fig. 10. First-stage assembly, clamped.

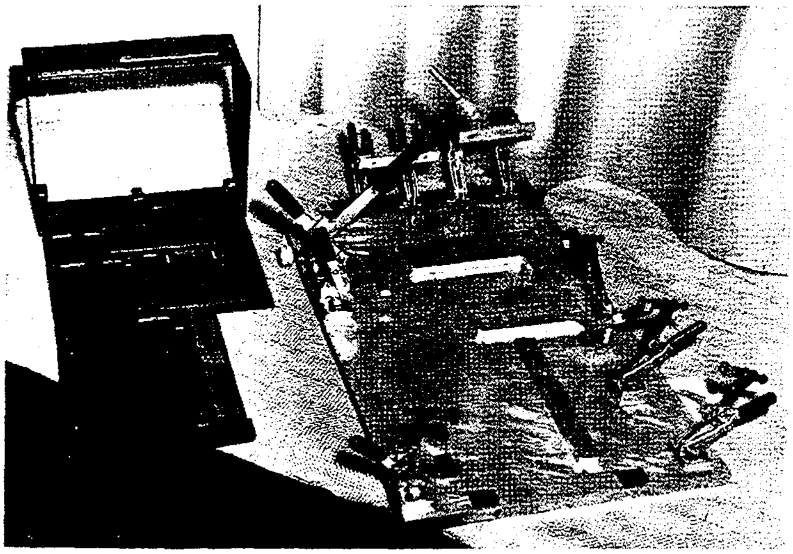


Fig. 11. First-stage assembly, completed.

Locating pads, support blocks, and spring-loaded clamps on bonding fixtures provide approximately 75 psi pressure on the bonded surfaces for good sealing and cure. Aluminum plate stock is used in preference to other materials, because its coefficient of expansion more closely matches that of the magnesium chassis components, thus reducing the change of excessive stresses by uneven forces. The fixture base plates are approximately 1-in. thick for strength and rigidity.

An oven-curing process was used for the first unit, although the fixtures are designed to permit installation of thermal cartridges and strip heaters so that the heat can be applied to the chassis while in an exposed condition. The ability

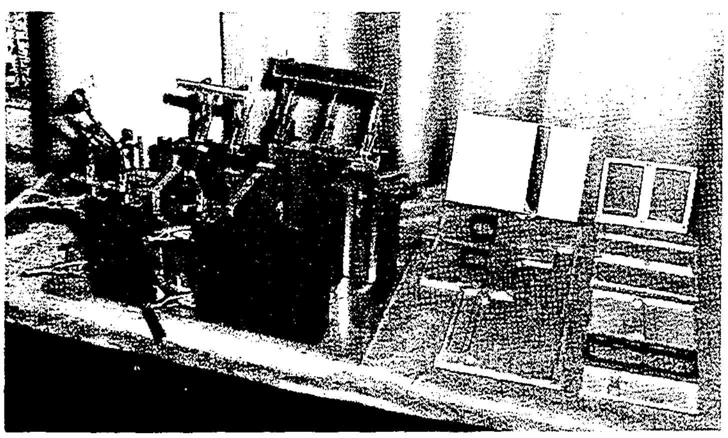


Fig. 12. Second-stage assembly, jig and parts.

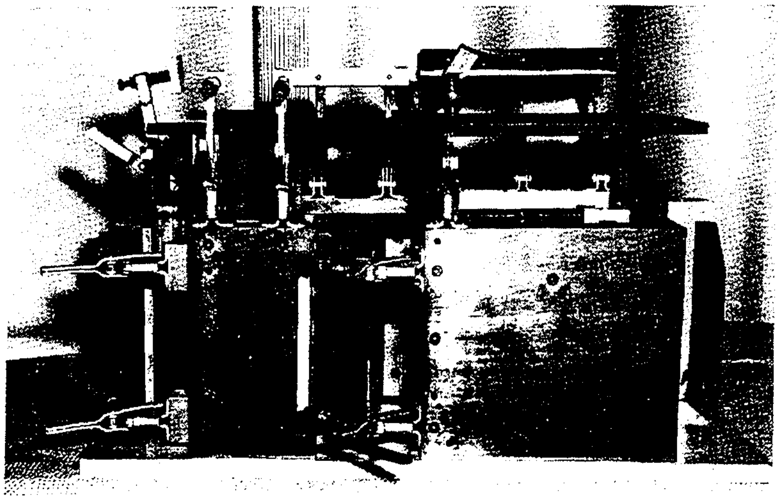


Fig. 13. Second-stage assembly, clamped.

to observe the unit while the adhesive is being cured would facilitate better production and quality control.

Prior to the first bonding stage, a sufficient quantity of the HT-424 adhesive film was removed from the low-temperature storage cabinet and allowed to warm up to room temperature before handling and cutting into the required strips to fit each bonded area. This particular adhesive should be stored at 0°F when not in use, and no attempt should be made to handle or unroll it before it reaches room temperature, since it is very brittle. At a storage temperature of 0°F, the shelf life of this particular film is about 3 months.

As stated previously, the chassis components and adhesive film were handled only with clean white cotton gloves to prevent contamination. The fixture was loaded and placed in the oven. The temperature was brought up to 275°F in 2 hr (measured by thermocouples placed in the base of the fixture and adjacent to an

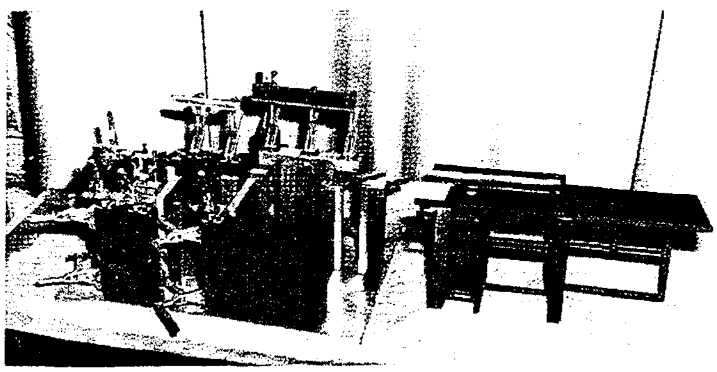


Fig. 14. Second-stage assembly, completed.

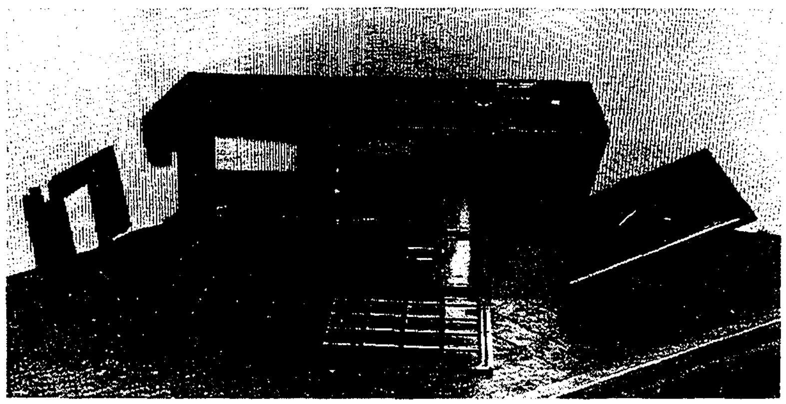


Fig. 15. Third-stage assembly parts, left side.

adhesive joint on the chassis). The temperature was then increased to the curing point (350°–355°F) and held for 45 min. Readings were taken from a recording controller throughout the heating and curing cycle, and the thermal lag between the fixture and chassis was kept at a minimum (average 4°F) to prevent the formation of any undue stress while heating. Lap shear test samples, clamped in a fixture at 75 psi pressure, were placed in the oven during the bonding operation to be used in pull tests to record the lap shear stress values of the bonded joints. After the curing cycle was completed, the fixture was left undisturbed in the oven until cooled to room temperature to prevent stress development.

Following completion of bonding, the critical dimensions on this subassembly were checked and found to be within 0.005 in. of stated overall dimensions. There was no distortion of the base plate, and the front housing maintained a true perpendicular alignment with the base plate.

The second-stage assembly was similar to the first-stage assembly using the same curing temperature. The third, or final, bonding stage was similar except that the curing temperature was reduced approximately 10°F (to 340°–343°F) and

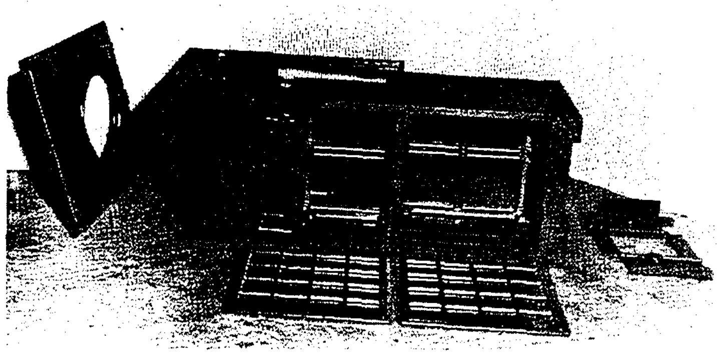


Fig. 16. Third-stage assembly parts, right side.

maintained for 50 min even though the specification for the adhesive does not require such a reduction for successive stages of bonding.

After the final bond was completed, the critical dimensions on the chassis were checked and found to be within 0.007 in. of the stated overall dimensions, well within the design tolerance of ± 0.015 in. The chassis was finish machined, including outer-perimeter holes for access covers and front and rear locating pin holes. All machined surfaces were touched up with Iridite 15, the entire chassis was surface sealed with Hysol (6101-J), followed by a vinyl resin zinc chromate primer (MIL-C-15328), and then painted with green strontium chromate.

LAP SHEAR TESTS

The test samples used during the several bonding operations were made of $\frac{1}{16}$-in. HK-31 magnesium strips approximately 3 in. long and 1 in. wide. Each sample was composed of two strips forming a $\frac{1}{2}$-in. lap joint bonded with 0.005-in. adhesive film and clamped together in a suitable holder at bonding pressure of 75 lb, the same value used in the bonding fixtures. These samples were tested. Unrestrained lap shear stress values were measured on a Tinius-Olsen Testing Machine. Typical results of these tests were:

Test Specimen	*Stress, psi*
1	1200
2	1400
3	1400
4	1200

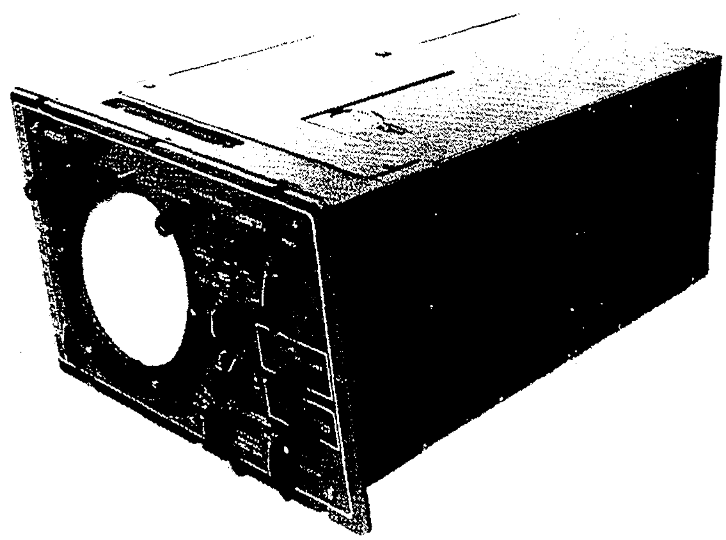


Fig. 17. Indicator—assembled.

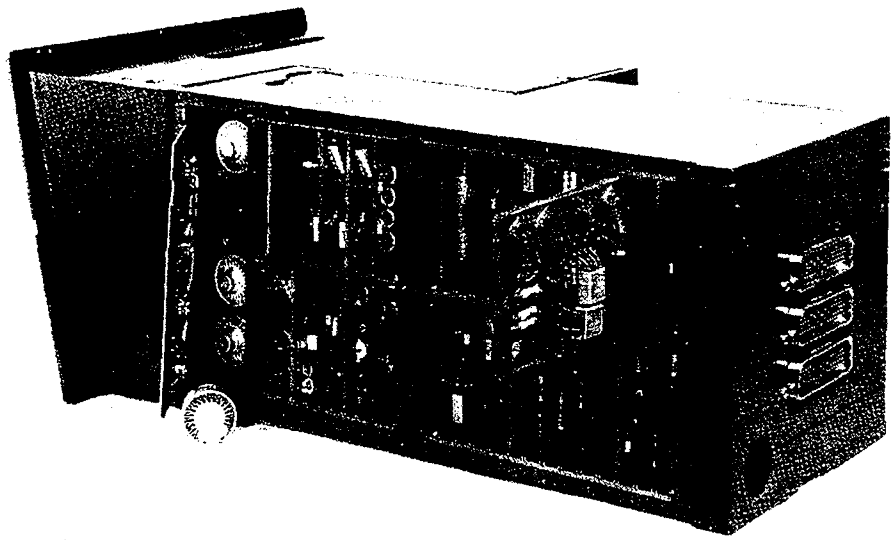


Fig. 18. Indicator, right side.

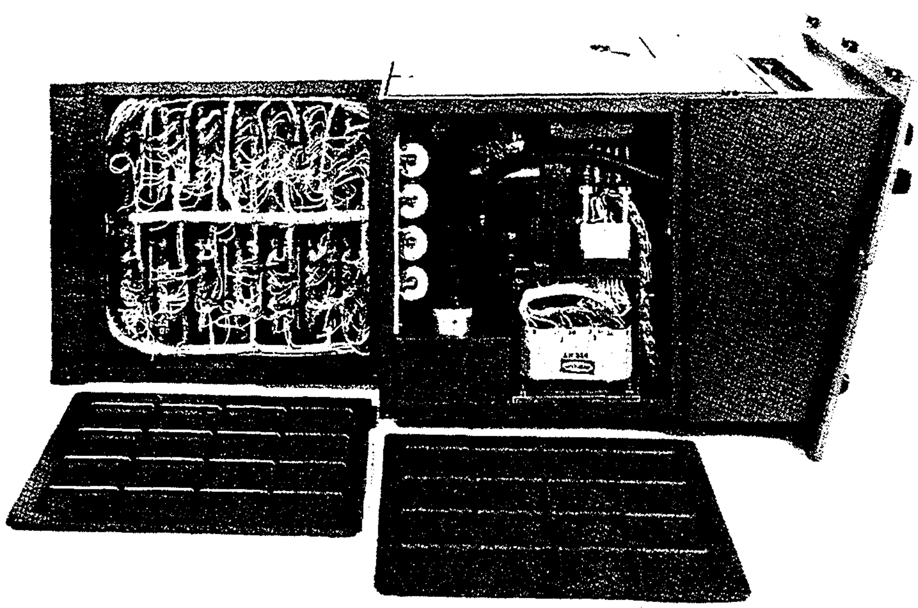


Fig. 19. Indicator, left side.

These results fall within the range given by the adhesive manufacturer's specifications, and agree with previous tests conducted by Raytheon.

The Indicator has been completely wired and assembled (as shown in Figs. 17, 18, and 19), and is now undergoing electrical and mechanical performance tests. Environmental shock and vibration tests will contribute valuable data for this type of chemically-milled, adhesive-bonded structure.

CONCLUSIONS

At the beginning of this program, the task of chemical milling, adhesive bonding, and fabrication of the chassis to be done by several vendors appeared to be formidable, but the enthusiasm, competence, and cooperation of all companies involved was extremely satisfactory and although the mechanical environmental tests will be the final proof, it is believed that the most difficult portions of the task are over.

VIBRATION TEST REPORT

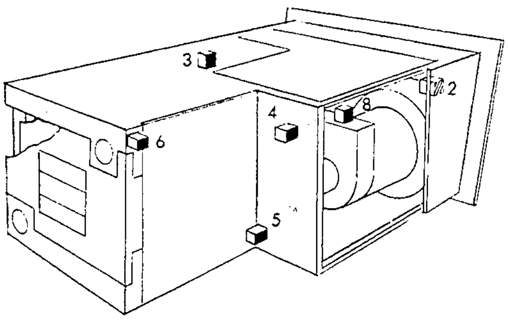
An Addendum

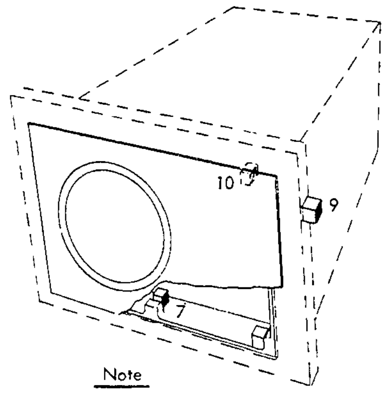
A limited series of vibration tests was performed on the Indicator to determine the effectiveness of the chemical-milling and adhesive-bonding techniques. Critical resonance points were examined to check the strength and rigidity of the design and to determine possible areas of improvement.

For a quick, overall evaluation, the unit was run through a cycle from 20 to 500 cps during a 15-min time interval, with 0.015-in. double amplitude from 20 to 62.5 cps and an input of 3 *g*'s from 62.5 to 500 cps. The unit was vibrated in three planes: vertical, major horizontal, and minor horizontal. To measure and record the vibration characteristics, nine pickups (Endevco Type 22–33) were located in various positions on the chassis as illustrated in Fig. A-1. Numbers 9 and 10 were control pickups attached to the mounting frame. The outputs from these pickups were recorded and results are shown graphically in Figs. A-2, A-3 and A-4.

The Indicator was complete and in operating condition but as the primary interest in this test was mechanical behavior the unit was not "fired-up" during test. The electrical circuitry was still undergoing "debugging," so the printed circuit boards were not oversprayed. However, upon completion of the tests, visual examination showed no broken leads or loose components.

Figure A-2, which is a record of the vertical axis vibration phase, shows the most severe resonance points (12 to 14 *g*'s) on pickups 4 and 5 between 90 and 200 cps. These pickups were located on the chemical-milled strut, a thin-walled structure 0.050 in. thick, forming the "dog-leg" of the chassis. This wall could be stiffened either by increasing the wall thickness or, preferably by adding a small rib across the center. Addition of the rib would be desirable because this area supports a heavy component board. Another critical point was at pickup number 7 located on the center of the lower front housing casting. This pickup indicated





Pick-up Number	Location	Note
2	Left front housing casting (top)	On solid casting wall approximately 1/4 in. thick
3	Top plate of unit-center (near main cross strut)	Placed to pick up main deflection of unit
4	On cross strut (dog-leg wall-top)	Thin wall member 0.051 in. thick
5	On cross strut (dog-leg wall-bottom)	Thin wall member 0.051 in. thick
6	Rear casting-top left side	Solid magnesium casting (1/4 in. thick)
7	Center of lower front housing wall (casting)	On 1/4 in. thick casting-unsupported (10 in. length)
8	Top of CRT casting	Record vibration of shock-mounted CRT assembly
9	Control pickup on right edge of test fixture front panel	To measure input to test fixture and chassis
10	On rear of dzus fastener on front panel of chassis	Control pickup

Fig. A-1

approximately 24 g's at 475 cps. This area very definitely needs additional strengthening.

Figure A-3, which illustrates vibration data in the major horizontal axis, exhibited no critical areas except at pickup number 7, where the results tracked fairly close with those in the previous vertical plane test.

Figure A-4, which illustrates the minor horizontal axis, behaved quite well

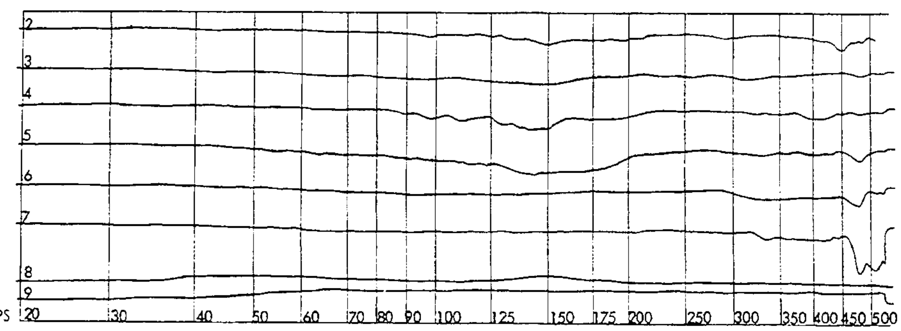


Fig. A-2. Indicator console unit vibration chart—vertical axis.

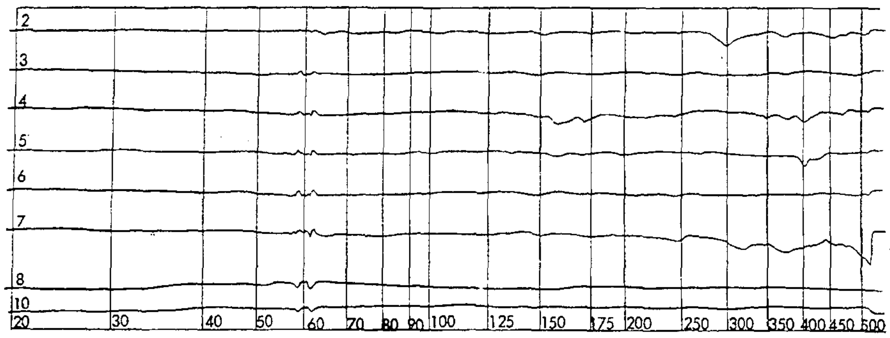


Fig. A-3. Indicator console unit vibration chart—major horizontal axis.

but confirmed the results indicating the need for stiffening the chemical-milled strut in the "dog-leg" area as evidenced in the vertical mode. (Note: It has been determined that the resonant indication at 275 cps on the monitoring pickups but not on the control pickups was caused by an electrical disturbance in the vibration system.)

The Indicator behaved well throughout the series of vibrations in the three planes. No sharply peaked resonance points were apparent anywhere on the recorder charts, indicating a reasonably constant performance over the range tested. During the test no sharp discernible noise frequencies were audible and visual examination upon the completion showed no structural, electrical component, or lead failures. It is recognized that this was only a 15-min cycling test but past experience has indicated that failures usually occur at resonance points or areas during this short time interval.

CONCLUSIONS

The utilization of the chemically-milled parts and the adhesive-bonded chassis achieved: First, a continuity of structure resulting in a good stress and load

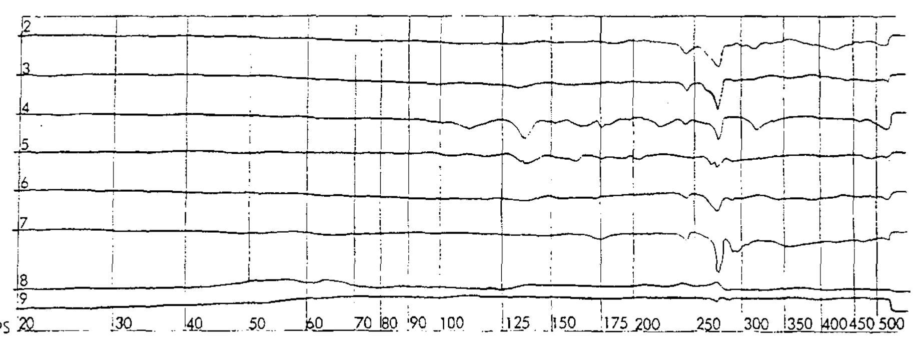


Fig. A-4. Indicator console unit vibration chart—minor horizontal axis.

distribution; second, the necessary strength-to-weight ratio and finally, the fulfillment of some of the critical airborne equipment requirements; namely, small size and light weight without sacrifice of reliability, serviceability, and high performance.

DISCUSSION

Q. (Russ Zimmer, Collins Radio, Cedar Rapids, Iowa). Mr. Karpuk, I noticed that it was mentioned that the chemical-milling process reached depths of about $\frac{1}{2}$ in. in some cases. I was wondering if, going to this depth, you ran into any problems in undercutting and if you did, how you managed to get around these.

A. No. We ourselves didn't run into any problems on undercutting. Chemical Contour Corp. in California did the job for us. The greatest thickness we used was $\frac{7}{8}$. We put generous radii throughout, in fact we overcompensated in our radii throughout the whole design and this was one of our design philosophies.

Q. (Martin Camen, Bendix Corporation, Teterboro, N.J.) Do you have any figures on cost of chemical milling *vs* standard machine operations for short prototype runs?

A. The cost comparisons we have is that the sheet metal casting unit cost us $2,400.00 to build, while this unit cost us $1,200.00.

Q. What tolerance can you hold on a chemical mill?

A. You can hold ± 0.010.

Q. (George Irvin, Jet Propulsion Lab., Pasadena, Calif.) I would like to know if you have ever tried to electroplate over adhesive-bonded joints, and if so, what was the character of the plating in the immediate area of the joint?

A. We have done no electroplating over chemical milling. I don't see any problems, but it would be recommended that the individual parts be plated before bonding as an assembly.

Q. (Harry Baker, Philco, WDL, Palo Alto, Calif.) Did you have any problem in selecting the film coating over the mag so as not to interfere with the bonding?

A. By the film coating, do you mean the Dow-9?

Q. Right.

A. Yes. We had some small problems. We ran through some tests without the film coating, and we found out that bare metal was the strongest method of getting the adhesive bond. This became impractical to leave around in the shop because of contamination. The difference between using Dow-9 and not coating was not that significant. So we went ahead and used Dow-9.

Q. This did not add an impurity into the bonding?

A. It does add an impurity—it does degrade it. I would call it a negligible amount.

Q. (Paul Andrus, Minneapolis-Honeywell, St. Petersburg, Fl.) How did you maintain electrical conductivity between the various magnesium piece parts when they were coated with the Dow-9?

A. We drilled, tapped, and put in terminals, and used jumpers.

Q. (Hank Cohen, Interstate Electronics, Anaheim, Calif.) In chemical-milling these castings, what effect does the etchant have on voids and inclusion in your material?

A. The only chemical milling done on the castings was to improve the surface finish.

Q. (Dick Snow, Hughes Aircraft, Culver City, Calif.) We are achieving electrical conductivity through bonded joints by the use of buttons of conductive epoxy put in the tape right at the time of thermal setting and it works out reasonably well for grounding strips.

A. Would this be an aluminum-filled modified epoxy?

Q. Yes. It is one of the Emerson-Cummings types, I am not sure which one.

A. We are considering studying that for some receiver work.

Q. (Leo Grizel, Nortronics, Hawthorne, Calif.) I was very much interested in the overall redesign. It looks like a real good job, but I was wondering if value analysis was used for the job or whether it was purely an engineering effort?

A. It was a crash program—value engineering was not involved.

Q. (Ralph Smith, U.S. Naval Ordnance Lab., Corona, Calif.) Did you chemical-mill this yourself?

A. Chemical Contour Corp., in Gardena, California, did the work.

Q. Do you know how small a diameter they can chemical-mill? How small a hole or slot can they mill?

A. Normally, holes are not chemically milled.

Q. (R. J. McMillan, Hughes Aircraft, Fullerton, Calif.) The statement was made on your specifications of a finish of 63, and you normally get 120. Now, the way I understand chemical milling, it is a direct function of the depth of chemical mill, and you cannot specify or maintain the finish unless you vary it with the depth. With aluminum, for example, the finish increases or gets rougher as the depth increases, and with magnesium it is just the reverse. Did you have any problems along these lines? Say you have a $\frac{1}{2}$-in. depth of chemical milling?

A. We didn't have any problems with the finish. We achieved a 63 finish on the bonded surface by machining. By chemically milling magnesium, you get a 125 finish on material to a depth of $\frac{1}{2}$ in. But there are various reports out specifying finishes utilizing different material and depth that I will be glad to show you.

Nr

Design for Automation

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This paper describes the packaging approach to miniaturizing a ground-based data processor to a size compatible with airborne applications. The project involved a volume reduction of 15 to 1 and a weight reduction of 25 to 1 relative to existing equipment.

INTRODUCTION

THE SPIRIT of competition often leads designers to seek innovations and manufacturers to establish new methods and tooling even under circumstances where the objectives do not require a new approach. An improved position can be gained by emphasizing the basic requirements of the program including cost, size, weight, and vested position in experience, training, and tooling. Innovations are of little value unless they bring with them the solutions of otherwise unsolvable problems. At the same time, designers must take advantage of newer materials, tools, and techniques, and must be sensitive to industry trends which could be advantageously applied to the assigned problem. Experiences on a specific program are reported in this paper which illustrate an approach to achieving a balance of advantages.

DESIGN REQUIREMENTS

The packaging problem as presented to the designers consisted of miniaturizing a ground-based data processor to the extent necessary to provide airborne capabilities. The original equipment, the AN/FST-2 Coordinate Data Transmitting Set, is of modularized construction utilizing vacuum tubes and a magnetic drum memory. Omitting displays, it occupies approximately 900 ft^3 and weighs approximately 15,000 lb. A modification, the Selective Identification Feature (SIF) was incorporated after the data processor was in full-scale production. This modification was transistorized and provided additional memory capacity by utilizing a 512-word 32-bit core memory. The new equipment to be designated as the AN/AYQ-1 Airborne Long Range Input (ALRI), while retaining all of the functional capabilities of the AN/FST-2, was limited to 56 ft^3 and 600 lb. This is a volume reduction of 15 to 1 and a weight reduction of 25 to 1.

In accordance with the usual requirements for military equipment, all designs must be in compliance with the applicable specifications and must be delivered on a relatively tight schedule. Study programs were immediately instituted with parallel efforts applied simultaneously in logical design, circuit design, mechanical packaging, and reliability. Identical requirements were imposed upon each group to ensure coordinated effort to meet the physical requirements, logical functions, reliability and maintainability aspects, and the environmental conditions.

STUDY OF AVAILABLE DESIGNS

The packaging designer, reverting to experience, found three possible packaging configurations: the transistorized SIF printed circuit cards, a concept known as the AN/ASB-8 (airborne computer) modules, and the Burroughs developed Macro-Module Chip (Fig. 1).

The SIF cards were 4 by 7 in. in size with printed circuitry on both sides and components mounted on one side. These circuit cards are being manufactured in large quantities using a highly automated production line. The cards were economical for use in all aspects except space, requiring approximately 25% more than the allowable volume.

The AN/ASB-8 modules utilized high-density packaging and welded construction after which the modules were embedded in epoxy to meet the requirements of airborne applications. This type of packaging if applied to ALRI could accomplish the task in approximately one-half the space allotted; however, the manufacture of the modules could not be automated. Further analysis of the tooling and production labor involved proved this approach to be too expensive for this application.

The Macro-Module Chip concept also looked attractive as the data processor portion of ALRI could be packaged in about 1 ft^3 of space with a weight of

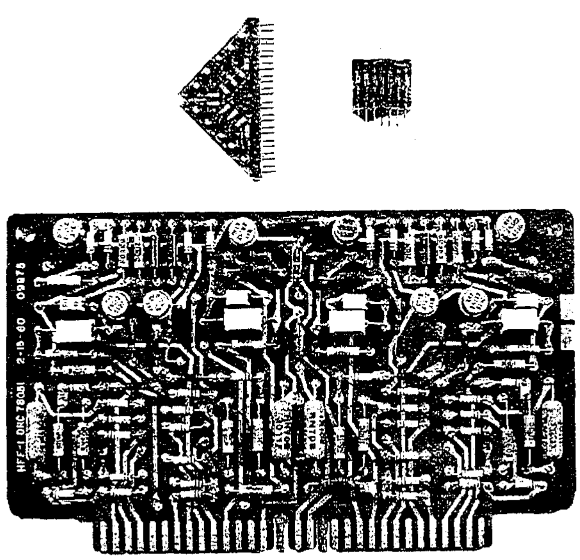

Fig. 1. Prior packaging methods.

TABLE I

Comparison of Prior Packaging Methods

	SIF	AN/ASB-8	Macro-Mod
Density	Low	High	High
Volume	75 ft^3	20 ft^3	5 ft^3
Weight	750 lb	550 lb	450 lb
Cost	Low	Medium high	High
Production experience	Abundant	Some	Little
Tooling available	Complete	Some	Some
Environmental capability	Satisfactory	Excellent	Excellent
Reliability	High	High	High
Maintainability	Good	Good	Good
Cooling	Forced air	Cold air	Coolant
Component availability	Shelf items	Some special	Little

approximately 130 lb. The component manufacturers had established industry standards for component size and ratings. Tooling had been started for automatic component insertion of the basic components: resistors and capacitors. Designs would be limited to a memory unit, compatibility circuits to cross-couple the memory unit to the data processor, and a heat exchanger to cool the data processor. However, further investigation revealed that components were available only in sample quantities at considerable expense, reliability of components was unknown, and tooling for automatic component insertion had progressed no further at that time than the study phase. This approach had to be discarded as untried and time-consuming.

DESIGN PROGRESS

Development of a new concept in packaging was initiated and the following factors were designated as the controlling considerations of any proposed design.

1. Cost
2. Size
3. Weight
4. Reliability
5. Maintenance
6. Shock and Vibration
7. Cooling

New ideas were given a quick review to determine compliance with the criteria and promising packaging methods were pursued to the extent of building samples of a basic circuit. The same basic circuit would be used for all samples to remove any variations of component costs. As each sample was completed, a review board composed of the Chief Engineer and representatives from Industrial Engineering and Purchasing analyzed each to determine manufacturing feasibility, labor costs, and tooling requirements. However, the samples continued to favor the size, component density, configuration, and hence, the construction methods of the AN/ASB-8 modules. Therefore, an additional requirement was imposed upon the designer: use the in-house automated facilities.

The module development program following the new criteria of design started with the high-density welded package with the fixed idea to reduce labor costs without materially increasing size. The first design approved for sample fabrication utilized a printed circuit plaque on the connector end of the module, while all other connections were spot-welded. A cost reduction was achieved while component density and size were retained. A second sample circuit was fabricated utilizing printed circuit plaques top and bottom, which resulted in a further cost reduction and indicated a possibility of dip-soldering. The chronological approach to various techniques are shown in Fig. 2.

The designers proposed that if the plaques could be made larger, increased use of automated facilities would further reduce costs. The small module was considered to be the largest nonrepairable subassembly; however, if the cost reduction could be made sufficiently attractive, larger subassemblies having the same packing density would be considered nonrepairable. Larger plaques could utilize the multiple-spindle Zagar drill if the printed circuit plaques were designed on a 0.100-in. grid pattern. Interconnections for logical signal and power wiring would be greatly reduced.

A sample module was constructed and presented to the review board for

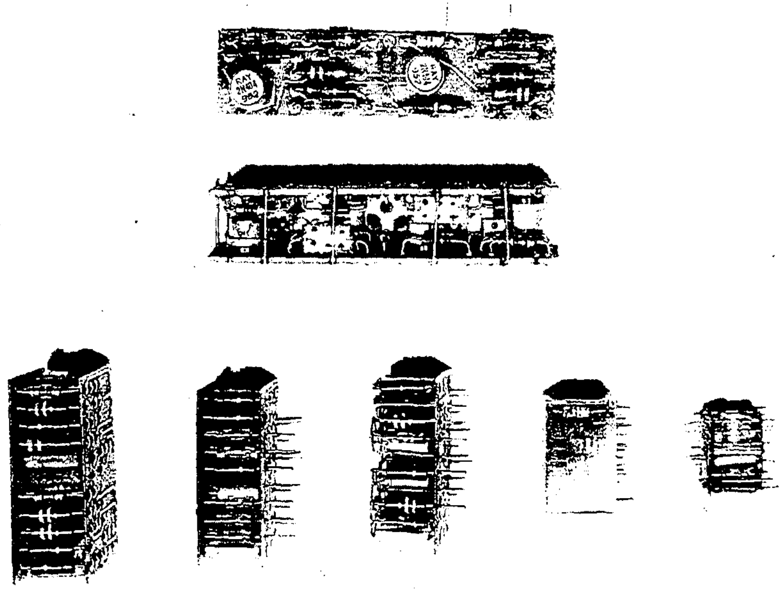

Fig. 2. Development samples.

analysis. The costs were reduced as anticipated; therefore, maximum component content of nonrepairable subassemblies was increased to 36 from 18. The volume of the larger package had increased slightly over the volume of two of the previous modules; however, the new modules were well within the system space limitations. Figure 3 charts the progress of the studies in two basic parameters.

The study programs involving logical design, reliability, and circuits had proceeded to the state where preliminary information was better than 90% firm. There was a reasonable certainty of the numbers and types of circuits required, new circuits had been breadboarded and proven, and reliable component parts had been selected for use. A semiselect 2N404 transistor in a standard TO-5 case would be used in most signal circuits and the associated component parts were military standard parts.

This led to the last and most important step in the design. If everything is standard, could the components be mounted by automatic insertion machines on each plaque rather than threaded between the plaques? Automatic component insertion would require a minimum of new tooling as the printed circuit facilities, the multiple spindle drills, and dip-soldering equipment had long been geared to work in conjunction with the automatic component insertion equipment. Two multiple station machines were available having approximately 20 stations each, as well as single-station component insertions. Plaques were quickly designed to become miniature component board assemblies with the plaques held together sandwich style by the circuit crossover connections. Several variations were made using open construction, single-station insertion of transistors, and multiple-station insertion of associated components. The success of the design was ensured; however, the automatic transistor insertion tools were not space-conservative and this item was discontinued. The open construction provided the cooling necessary by natural air-flow, while moisture and fungus-proofing was provided by a dip-coating of MIL-approved MFP varnish. An analysis of these modules proved them to be

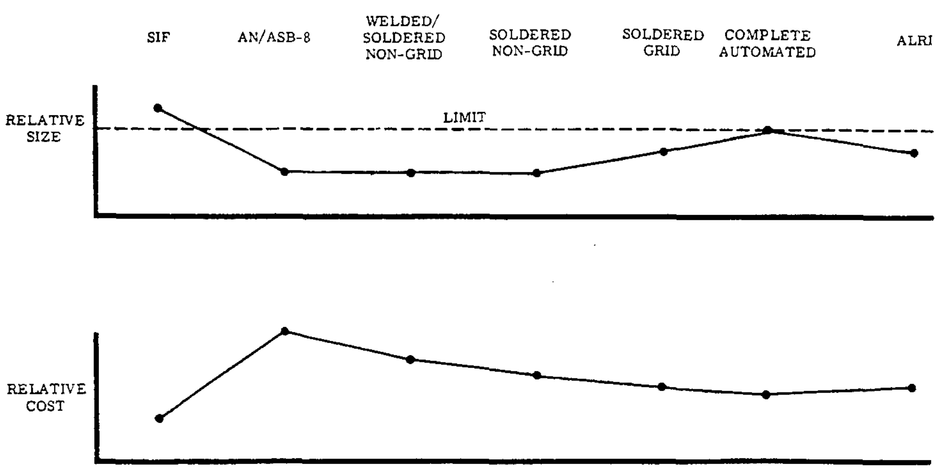

Fig. 3. Progress chart of design analysis.

economical through ease of assembly and test while requiring no new tooling. The component density was somewhat less than the original AN/ASB-8 configuration but approximately double that of the normal automated printed circuit board.

The ALRI module as derived by these steps in design is made in three sizes, differing only in the length of the module. Basic dimensions of the modules are: 0.6 in. wide, 0.8 in. high, and lengths of 1.8, 2.4, or 2.75 in. The printed circuit boards for the modules have plated-through holes, which have been grid-drilled for component and external lead mounting. Additional plated holes were provided where necessary for circuit feedthrough on each board while paired plated notches were provided for board-to-board crossover ties. Material for the boards is $\frac{3}{64}$-in.-thick paper epoxy, which was selected for machinability, moisture and fungus resistance and self-extinguishing flame characteristics. Typical production modules are shown in Fig. 4.

Where possible, standardization of component location was maintained resulting in identical component assemblies for the two halves of the sandwich construction; this standardization ensured longer production runs on the automatic component insertion equipment, to insert tipletted diodes, resistors, and external connection leads before equipment readjustment for additional components became necessary. Tiplets are triangular metal particles which become truncated pyramidal in shape when positioned and swaged on component leads. The automatic

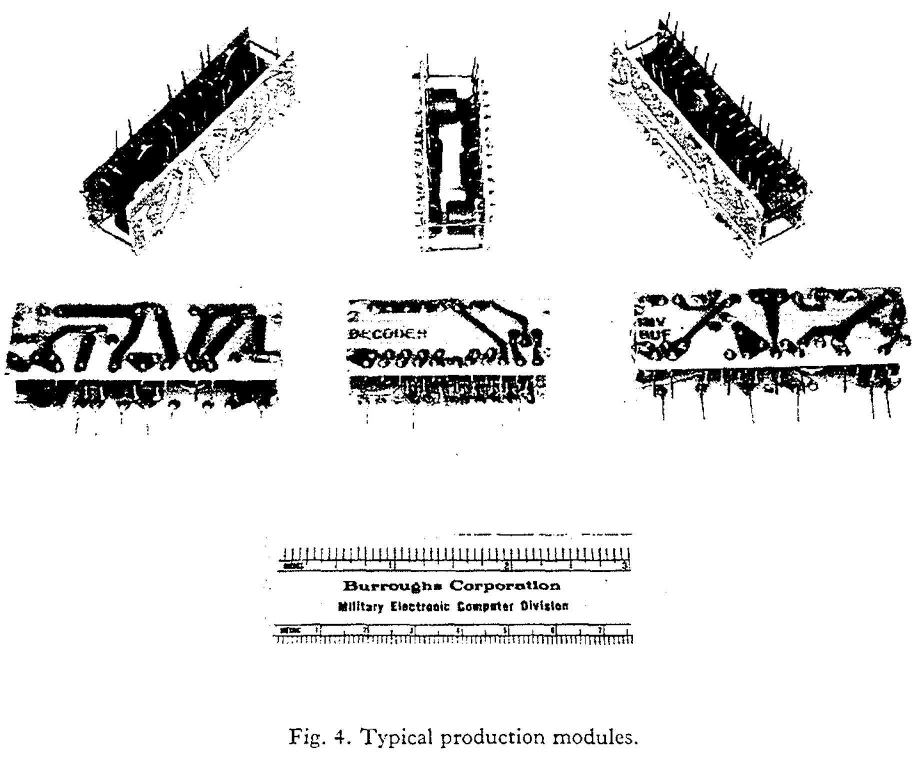

Fig. 4. Typical production modules.

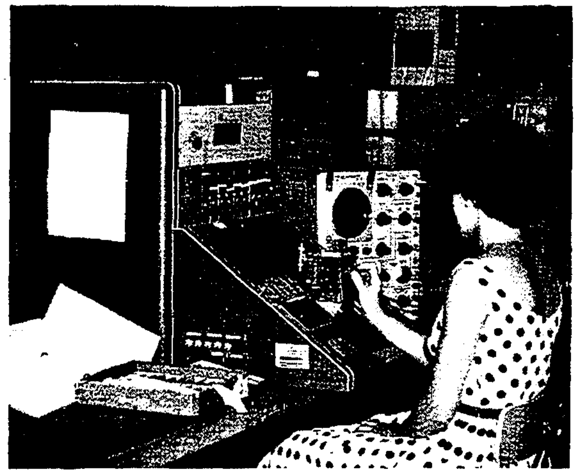

Fig. 5. Module test station.

insertion equipment drives the lead tiplet into the plated-through holes in the printed circuit boards, providing a secure electrical and mechanical connection prior to soldering. Of interest is the fact that the remainder of the diode leads that are trimmed from the belted and tipletted diodes are salvaged and are automatically inserted at another station to provide the leads for external connections.

The remainder of the component parts are manually inserted as the first step of final module assembly. These are the components such as transistors where it had been determined that tool clearances necessary for automatic insertion were not conducive to high packing density. The two halves of a module are then fixturized and the crossover ties provided a rigid mechanical assembly as well as electrical interconnection of the sandwich. The assembly is then dip-soldered after which it is tested by plugging it into an automatic test fixture. Figure 5 shows a test station with an individual module in a test fixture. Upon successful completion of all visual inspections and electrical tests, the modules are given a dip-coating of MFP varnish which completes the processing of the module.

CORE MEMORIES RECONFIGURED

Packaging of the core memory was also accomplished by utilization of the techniques developed for the logic elements. The core planes are assembled on printed circuit boards which have had terminals pressed into plated-through holes and dip-soldered to the board. A special memory switch diode module 0.6 in. wide by 0.5 in. high, by 2.1 in. long and patterned after the logic modules is assembled on the associated core plane board assembly. The core plane assemblies have a 64-pin connector tab, top and bottom, which is plugged into printed circuit connectors dip-soldered to a printed circuit backboard and a printed circuit interconnection board as shown in Fig. 6.

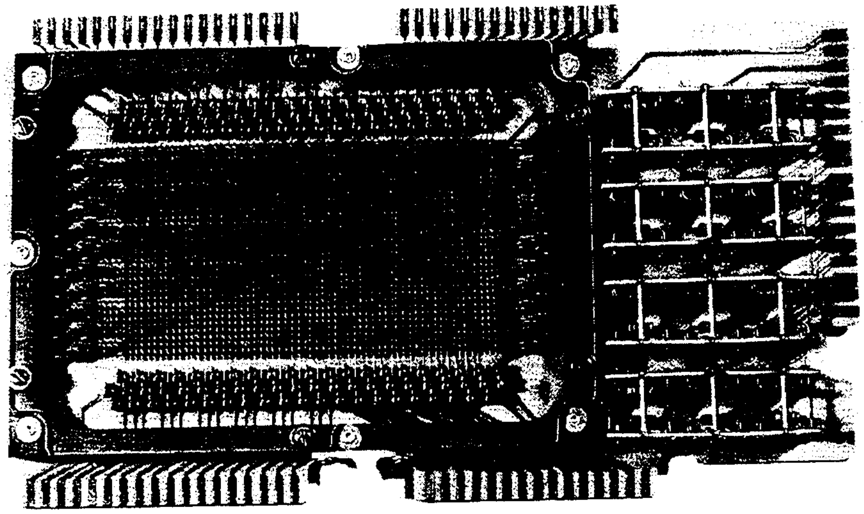

Fig. 6. Core plane assembly.

FUNCTIONAL MODULARITY

Further development determined that judicious placement of these modules, now known as Logi-Mod Modules, into discrete functional logical groups provided a pattern which would lend itself to additional simplification of interconnection wiring. Attempts to use printed circuitry for such interconnections proved successful and the resultant master assembly boards of Fig. 7 became known as mother

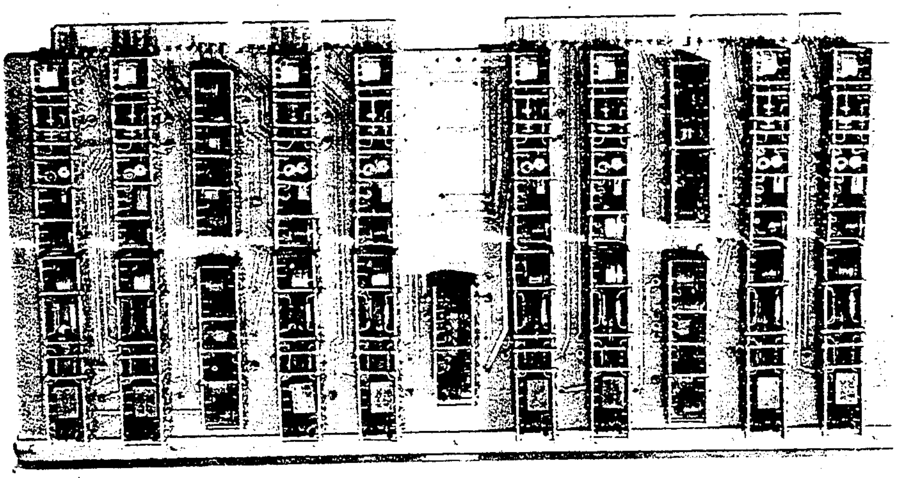

Fig. 7. Module mother board.

Fig. 8. Mother board test station.

boards. These boards are $\frac{1}{16}$ in. thick by $6\frac{3}{8}$ in. high, by $13\frac{1}{4}$ in. in width and are of epoxy paper with tabs for two 60-pin printed circuit connectors. These boards also utilize plated-through holes for circuit feedthrough; however, the module leads pass through plain holes and are folded over onto printed circuit pads adjacent to the mounting holes prior to dip-soldering. This method of mounting provided a simplified means of removing and replacing modules since the leads may be unsoldered and unfolded one at a time, permitting easy withdrawal of a module. A test panel for a mother board is shown in Fig. 8.

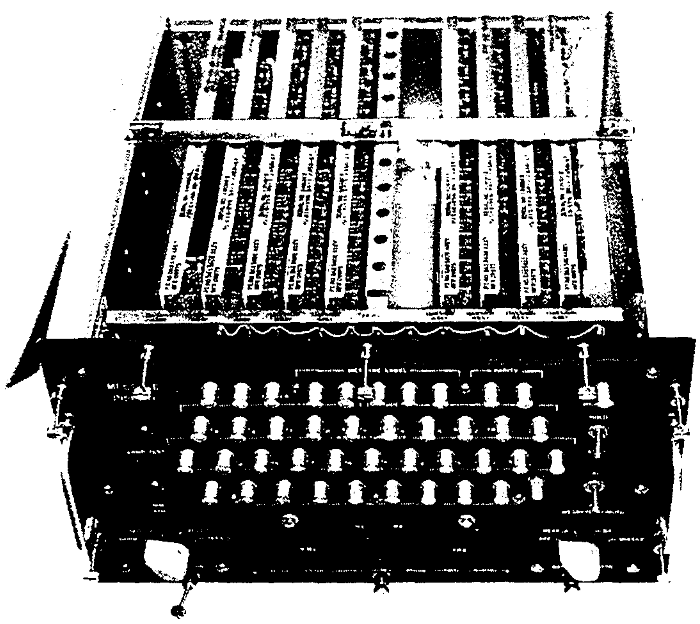

Fig. 9. Chassis assembly.

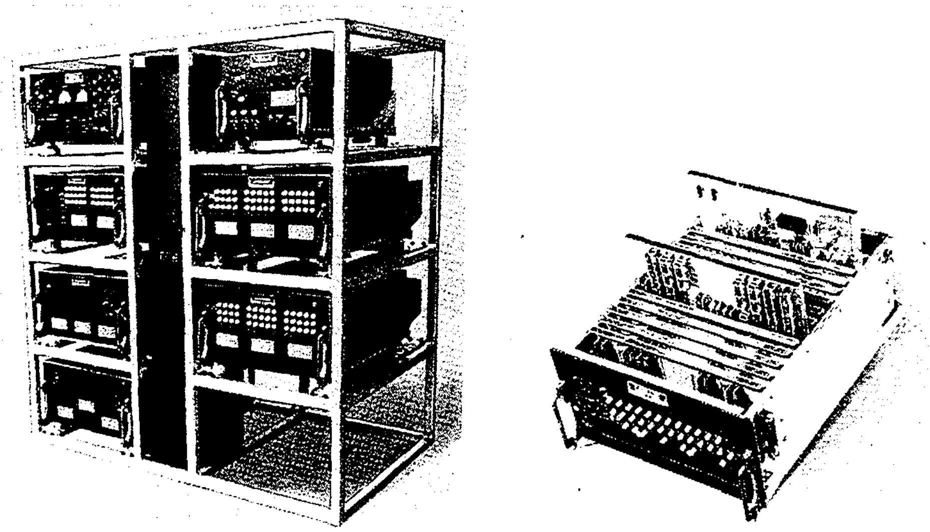

Fig. 10. AN/AYQ-1 ALRI data processor.

The completed mother boards plug into the printed circuit connectors which are mounted within an ATR chassis as seen in Fig. 9. This chassis in turn is mounted by the use of vibration isolators in a rack designed for the aircraft. Thus, it can be seen that wiring interconnections for the modules are nonexistent, while the interconnections for the mother boards may be harnessed, after which the entire harness assembly is positioned and bolted into the ATR chassis, or the interconnections may be wired after the connectors are assembled. Cable assemblies interconnect ATR chassis to form the completed equipment as shown in Fig. 10.

CONCLUSION

The packaging concept resulting from the program discussed successfully met all economic and equipment requirements. Although participation in "advancing the state of the art" was an initial desire of both the engineering and manufacturing activities, this desire was successfully suppressed and a more realistic goal attained. An analysis of available in-house automation facilities was an important factor which led to economical fabrication and assembly. Parallel efforts in electrical, logical, and packaging design along with the breadboarding of development samples resulted in the timely start-up of product fabrication. Initial in-house testing and subsequent in-flight test acceptance attest to the reliability and environmental soundness of the design, as well as to its meeting with the functional requirements.

ADDENDUM

Since one of the major factors which determined the finally selected design was the existence of automated facilities, it is appropriate to identify these facilities in a pictorial guided "tour." This tour will be conducted in the same chronological sequence that is followed as a printed circuit card progresses from paper epoxy with copper foil on both sides to a finished, dip-soldered assembly. Those facilities more commonplace in nature such as shearing, blanking, and minor hand assembly are purposely omitted as being of no particular interest when compared with the automated facilities. Also, the chronology of re-entry into the plating facilities after silk-screening of plating resists or second and subsequent passes on automatic component insertion will not be attempted.

Component mounting and circuit feedthrough holes in a printed circuit board are drilled in the multiple spindle Zagar drill shown in Fig. 11. This machine is capable of drilling 1500 holes simultaneously to exacting dimensions in phenolic, paper epoxy, or glass epoxy copper-clad stock. Nonplated holes such as used for mounting modules on the mother boards are drilled here also after the plating processes have been completed.

All plating and associated processes are performed in the plating room shown in Fig. 12. Short-run items are processed in the tanks shown on the left of the picture while automatic plating equipment with the conveyor line may be seen through the vent stacks to the right rear of the picture. This equipment is capable of performing copper deposition, copper, solder, nickel, gold, and rhodium plating at a high reliability, high volume level. Solder-plating, it may be noted, is used on the circuitry as the etch resist. Other equipment provides for etching, stripping, sanding, scrubbing, drying, and flush circuitry processing. A storage and mixing area has five tanks with interconnecting plumbing to expedite the mixing and transfer of solutions.

The silk-screen area shown in Fig. 13 includes a silk-screen fabrication room and the screening room. These rooms are temperature- and humidity-controlled

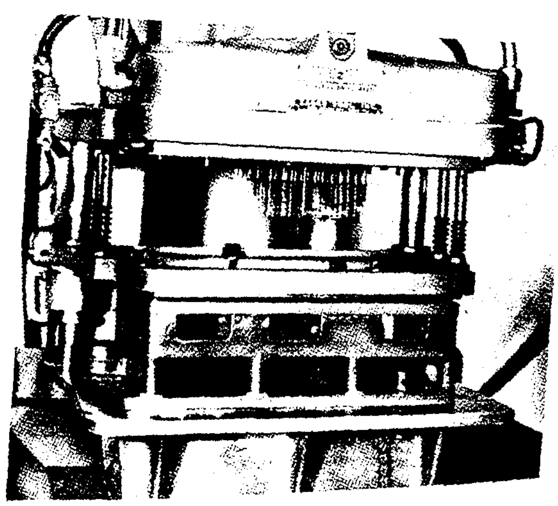

Fig. 11. Multiple spindle Zagar drill.

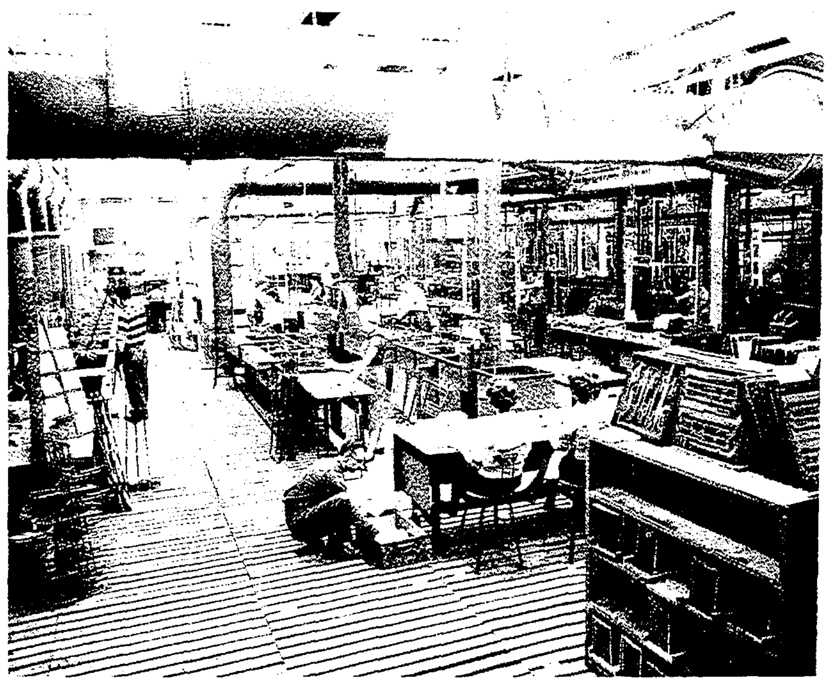

Fig. 12. Plating room.

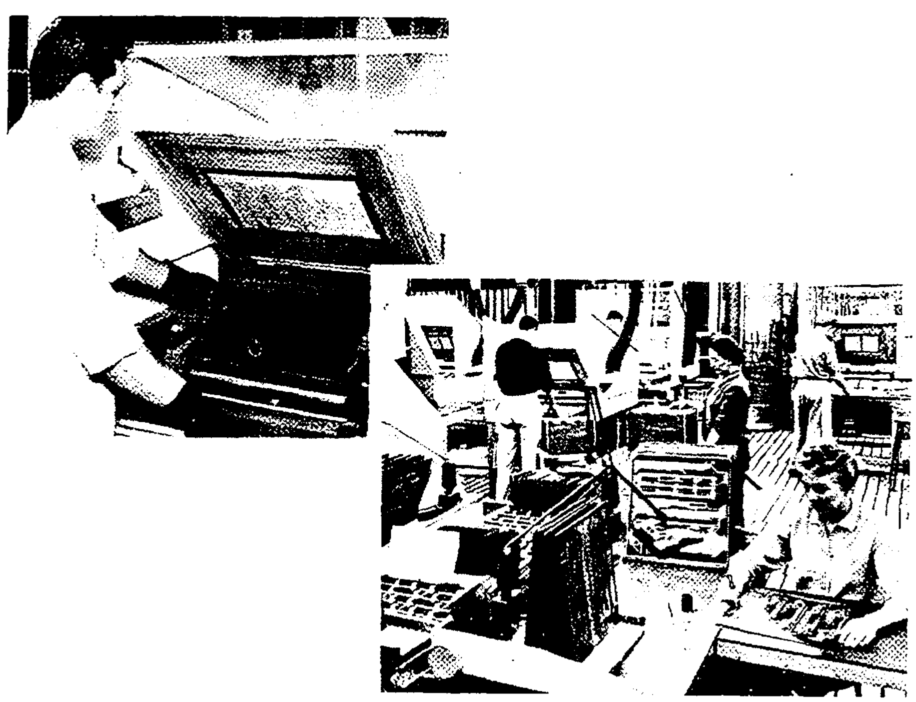

Fig. 13. Silk screening.

to retain dimensional stability throughout the process. Hooded work stations aid in operational cleanliness. Plating resist is screened on the boards after the through holes have been copper-plated and prior to solder plating.

Automated components assembly is accomplished on the machines shown in Fig. 14. Automatic insertion requires that the components be properly spaced

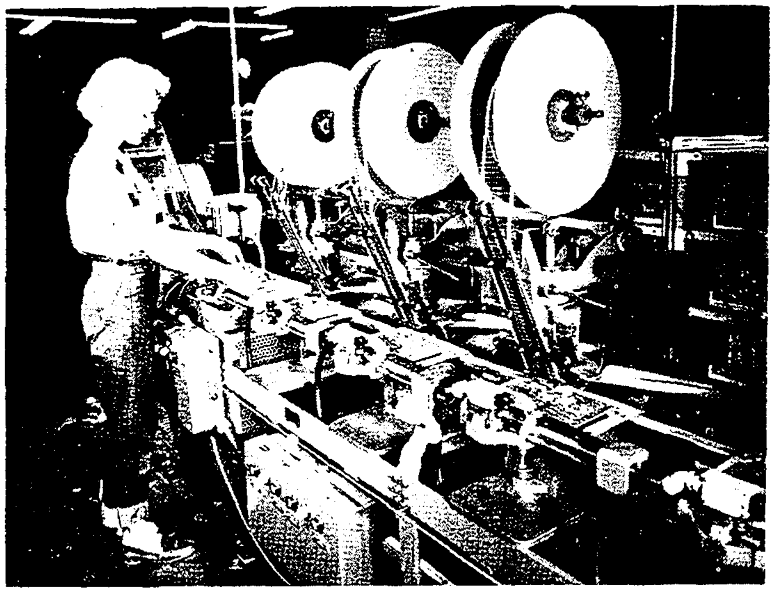

Fig. 14. Tipletting and assembly of components.

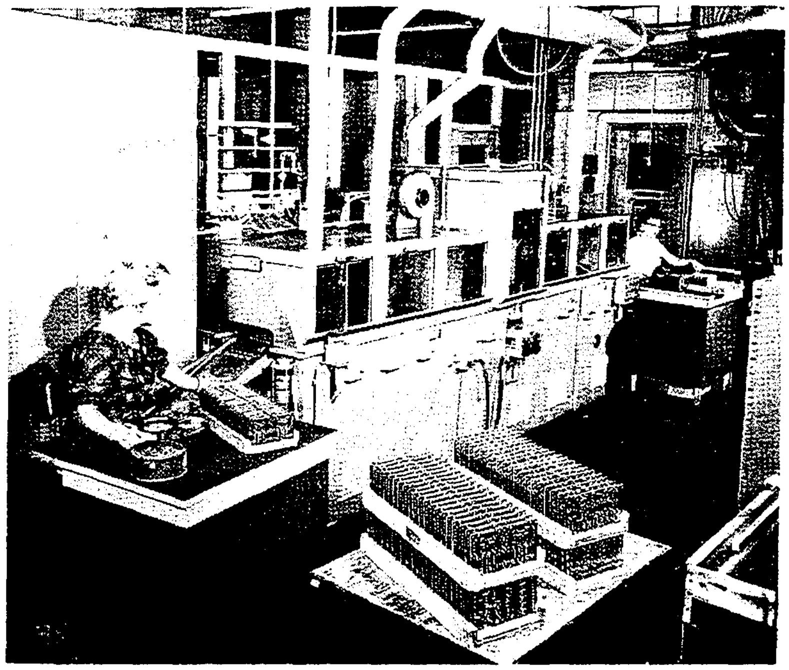

Fig. 15. Automatic dip-soldering.

and taped on a belt. This is shown in the picture on the right. For double-sided circuit boards such as used on the ALRI program, the belted components are then fed through the tipletting machine which swages a tiplet on each end of the component. At the insertion station the component is sheared to length, formed, and inserted in the printed circuit board. Several stations of the line are shown in the picture on the left.

Automatic dip-soldering equipment is shown in Fig. 15. Each printed circuit component assembly is fluxed, soldered, scrubbed, washed, and dried as it passes through this machine. With solder temperatures and cycling time accurately controlled, all component assemblies are soldered uniformly at a rate up to 250/hr.

DISCUSSION

Q. (Max Alper, Gianni Controls, Duarte, Calif.) Was the insertion of the modules into the mother boards automated?

A. No. This has not been automated.

Q. Is there any sort of protective coating used on the assemblies?

A. The modules are given a dip-coating of MFP varnish for additional moisture and fungus-proof resistance.

Q. Any further coating on the mother boards after assembly?

A. The board assemblies are now also given a coating of MFP varnish.

Q. (Gene Segerson, Motorola, Phoenix, Ariz.) I have noticed that most of you fellows have talked about throwaway modules during this seminar and I am curious as to the price range. What do you consider the fair price to throwaway? Where do you draw the line, and I wonder if anyone else has any comment on that also?

A. Well, I would say the price of a throwaway item at one time was \$100 and then \$50. We consider a throwaway module to be of this type here, costing in the range of \$10 to \$20, depending on the cost of the components which go into the module. Again these modules can be repaired to some extent, depending on the value of the components.

Q. (Pete Gerlach, Automatic Labs., Northlake, Ill.) You mentioned that the components were automatically inserted in the original assemblies. Did you develop your own insertion equipment or was it commercially available?

A. We used "Dynasert" equipment, which came from United Shoe Machine Corporation. It has been modified by us for our use. We have two lines, one of 17 stations and one of 28 stations, plus individual "Pantosert" stations. We use the identical head on a Panto table for small production runs, rather than set up a long production line. Many times it is economical to use a Pantosert when there is a group of similar components, such as diodes. They can be stepped along and inserted with the Pantosert.

Q. (Joe Ritter, Electronic Modules, Timonium, Md.) I wonder if you could elaborate a little bit on the cooling; the picture wasn't too clear, but I believe you said the cooling came up through the module, then when you showed the reverse side, it looked like it was all blocked off with the connectors and panels.

A. No. There are slots between the connectors to facilitate airflow through them. Each chassis, incidentally, has its own blowers, for additional cooling, and heaters. One of our problems was coming up to operating temperature in the minimum time, especially in the memory section, which is quite heavily packed.

Q. (Al Acken, RCA, Van Nuys, Calif.) What advantage did you gain by placing two planes back to back? Couldn't that just as well have been packaged as individual modules on the mother board?

A. Are you talking about using just a half module or one wafer?

Q. You have two wafers that are mechanically connected with a riser wire. Did you gain any advantage by doing this?

A. We have approximately doubled the component density over a normal automated printed circuit board.

Q. I don't understand this. It seems that you could take these and mount them individually to the mother board in the same position. Why are they mechanically connected together?

A. To make them logical function modules—in other words, a complete flip-flop.

Q. Oh, there is electrical connection between the two.

A. Oh yes, the crossover wires are not only mechanical, but also electrical interconnections.

Q. (Frank Rhodes, Aerojet General, Azusa, Calif.) I would like to know what the length of time was for this development program.

A. The module development program itself was approximately 60 days.

Q. (Harold R. Overman, ITT, Ft. Wayne, Ind.) I notice that the similar types of modules covered previously in this Symposium have invariably been encapsulated. Would you care to comment on that?

A. We found these assemblies quite rigid with the crossover ties which are used on the module, making it unnecessary to encapsulate. We had sufficient shock and vibration resistance, and encapsulation would have put us overweight. Additionally, the MFP varnish dip-coat adds resiliency to each of the components mounted in the modules.

Q. (Ed Cormier, General Dynamics/Astronautics, San Diego, Calif.) I would like to take this opportunity to congratulate Burrough's Corporation on their part in the Mercury-Man-In-Space Program and in defense of the Free World. The size of a welded module *vs* the final soldered configuration appears in Fig. 2 to be approximately 50% greater for the soldered module. This is also indicated on the curve of Fig. 3 and presumably does not take into consideration the strong possibility that encapsulated welded modules would not require vibration isolation which this equipment had. I wonder what the procuring activity would have been willing to pay for an additional 14 or 15 ft^3 of prime usable space in their aircraft?

A. I can't answer on cost *vs* space for the customer. When we were given this we were actually on a fixed-price contract. Our research center in Paoli was the prime contractor and we were allowed this particular volume; being on a fixed price we made it as economical as we could. You made another statement there, something about the one being twice the volume of the other.

Q. Fifty percent greater for the soldered module it appeared to me. And the chart in Fig. 3 said about the same thing. We started with a welded module half the size of the allowable and then you wound up with $\frac{3}{4}$ the size of the allowable; the allowable being 60 ft^3.

A. We came in at somewhere around 50–52 ft^3. The welded module would have been slightly smaller, but it would have been considerably heavier. By the time we considered power supplies and all other equipment we would have exceeded the restricted weight.

Q. I gathered from reading the paper that if someone hadn't come along and said use in-house facilities, which some of us don't have, you would have been talking today about a welded module success.

A. We had already used welded modules at our facility and I said we, like other people, like to compete in this state of the art. We like to make really small modules also, but this became a point of economics rather than a competition in the state of the art.

Q. (Al Gaetjens, General Electric Co., Valley Forge, Pa.) How much electrical redesign of these circuits was necessary to change from the ground configuration to the final configuration?

A. I don't believe there is much comparison at all. There is practically a complete redesign in circuitry—not in logic. We had to achieve the same functional capabilities, but how we did it was our own choice. Therefore, we utilized circuitry which had been developed in other projects, but not the original circuitry.

Q. (Joe Ritter, Electronic Modules, Timonium, Md.) I would like to comment on the last comment by the gentleman there. It seems to me in this design there are other parameters that justify going to the soldered module, things like using automated equipment. Had the design objective been just small size, this module could have been made soldered just as small as the welded module. This is one of the points we tried to make at the meeting the other night, and I think it is an unfair implication to say that a welded module would be 50% smaller.

A. Thank you. The paper also mentioned soldered modules of the same size as the welded module.

Status Report: "Swiss Cheese" Method of Circuit Packaging

BOB G. BENDER AND ROY W. DREYER

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This paper describes a microcircuit fabrication technique known as "Swiss Cheese." Circuits are built up from pellet-shaped components without leads. The principal charm of the method is its extreme simplicity and flexibility. Compact, rugged design, which is compatible with automatic assembly, and the assurance of high reliability make this method advantageous.

INTRODUCTION

"SWISS CHEESE" refers to the microcircuit fabrication technique which arranges pellet-shaped components, of constant thickness and variable diameter without leads, into useful electronic arrays within an insulating substrate of like thickness (see Fig. 1). Interconnecting circuitry is carried on both major surfaces and threaded between the surfaces by the devices functioning as feedthroughs.

The purpose of this paper is to bring people up to date on the development of Swiss Cheese, and also to acquaint others who have not yet heard of the technique with the assembly details and the present technological status.

The basic idea behind the Swiss Cheese fabrication was conceived over three years ago in the Hughes Laboratories. Since that time, a substantial amount of work has gone into the improvement of the quality and availability of devices, and also to provide several simple techniques by which devices could be intraconnected within a circuit card. The problem of interconnecting wafers or modules has also been the target of study. Approximately twenty internal publications have been written on these subjects at Hughes, of which at least nine have been published; a bibliography is appended.

MICROSEAL PACKAGING

The principal contribution of the authors was the development of packaging techniques for the Hughes Microseal* diode and transistor shown in Fig. 2, and

*Trademark, Hughes Aircraft Company.

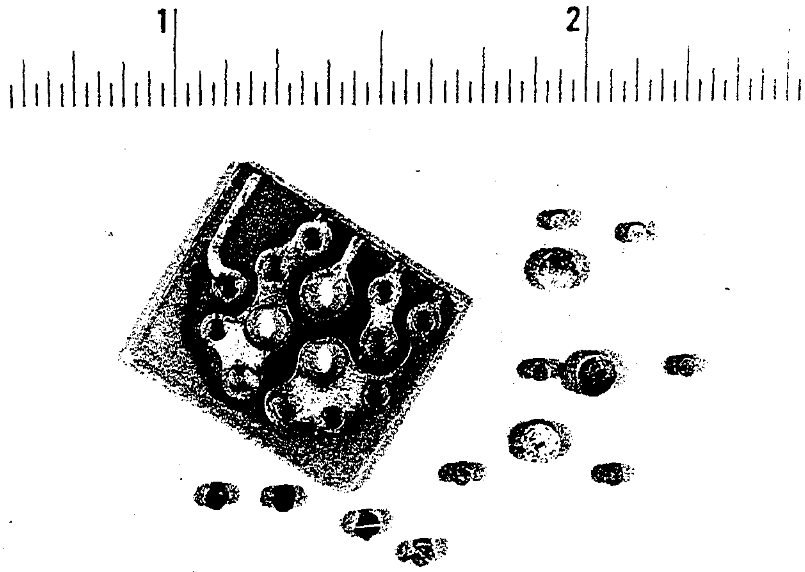

Fig. 1. Swiss Cheese circuit board and components ready for assembly.

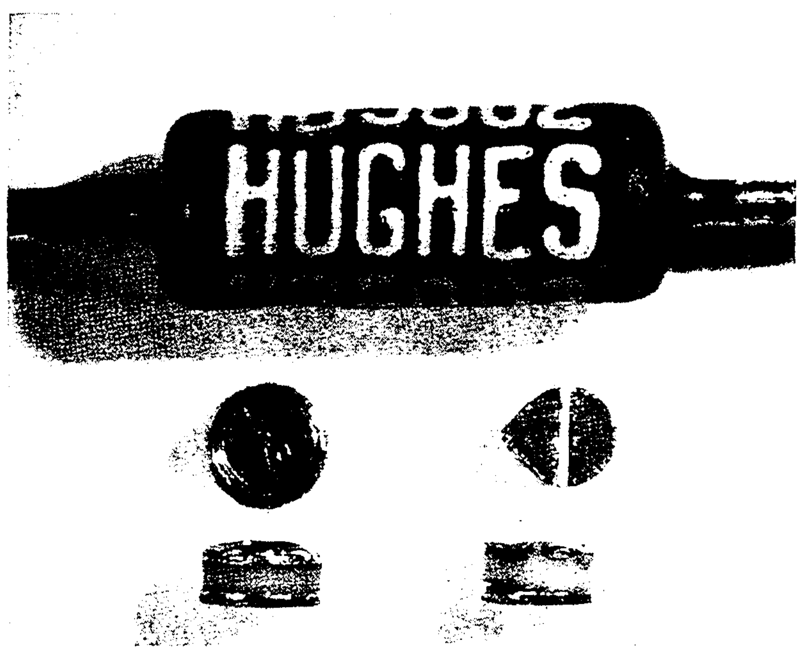

Fig. 2. Microseal diodes and transistors.

cross-sectioned in Fig. 3. Both device structures are similar in that they are composed of a metallized ceramic housing into which the semiconductor device chip is placed, and to which metal electrodes are alloyed, thereby performing the dual functions of contacting of the various semiconductor conductivity regions and hermetically sealing the enclosure.

During the early development phase, the rather complex shape required for the Microseal transistor was fabricated at Hughes by ultrasonic machining of the soft-fired ceramic material. After final forming, the part was metallized in the green state. Thus, one firing process accomplished the maturing of the metallizing as well as the body. After firing, a suitable plating is applied to the metallized surfaces (Fig. 4). The housing with the semiconductor device chip and the electrodes meet in a jig and all attachments and seals are accomplished in a single-furnace operation. A low-temperature fluxless brazing alloy is used to seal the joints.

The electrode materials are unique in that they are clad with their own brazing and alloy, thereby eliminating the necessity of handling separate preforms. This technique also eliminates one seal at each end. The top cap of the Microseal diode is tantalum, clad on both sides with gold, and then clad again on both sides with tin. In the assembly process, the tin melts first and begins wetting the metallized regions of the ceramic body, and also the regions of the semiconductor chip. When the molten tin appears, it begins to dissolve gold from the clad layer underneath it. At 280°C tin and gold equilibrate to produce an alloy with 80% gold and the balance tin. This means, then, that the first appearance of the liquid phase on heating is at 232°C, the melting point of tin. On cooling, total disappearance of a

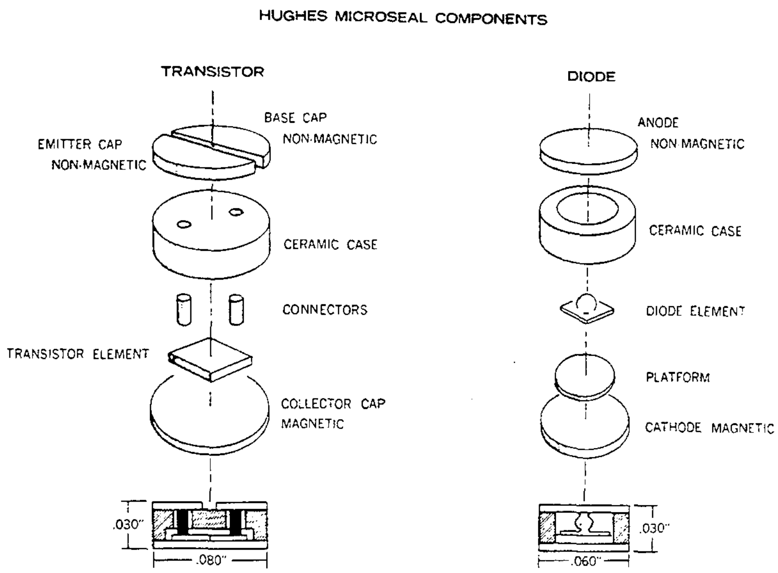

Fig. 3. Microseal diodes and transistors (assembly drawing).

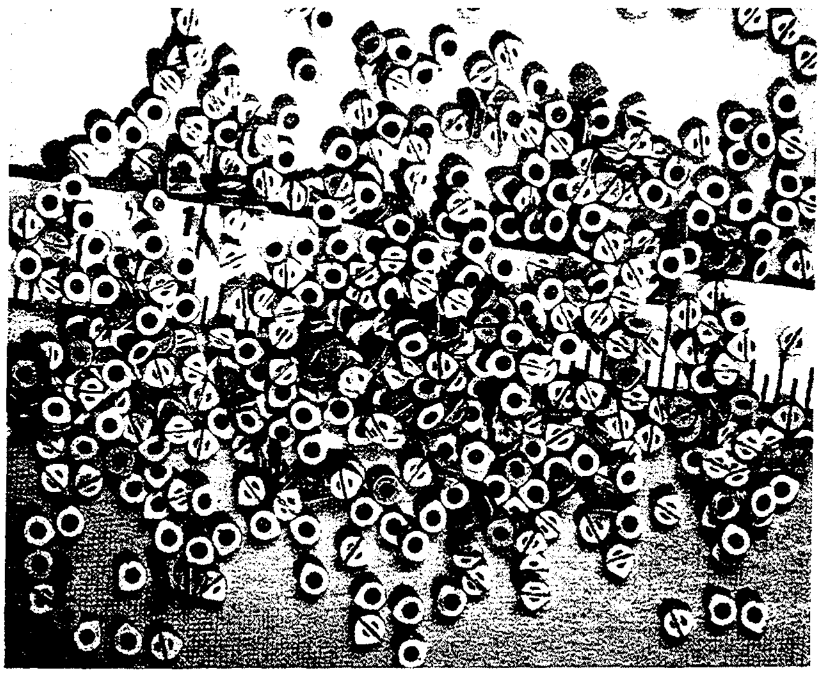

Fig. 4. Microseal transistor housing.

liquid phase occurs at 280°C, thus limiting the plague of solder closures known as "suck and blow."

Devices fabricated by this technique have been tested by the Radiflow leak-detection method, which on a routine basis is capable of measuring leak rates down to 2×10^{-11} atm-cc/sec of standard air. Using the Radiflow to study the profile of the product coming from our production lines, we find the bulk of devices have leak rates lower than Radiflow is able to detect. However, we have been able to establish a correlation between device survival of 10-day temperature and humidity cycling, the MIL Standard 202, Method 106, and leak rates less than 10^{-10} atm-cc/sec.

Power Dissipation

In view of their very small size, the power dissipation ratings of Microseal devices, Table I, will surprise many readers. These ratings are accomplished by alloying the device itself to a very thin metallic member. Thus there is very little resistance to the flow of heat from the junction to the outside of the package.

Available Components

Table II is a chart showing the ranges of the passive and active components currently available, including power ratings, sizes, and some indication of prices. The purpose of this table is to show that a variety of components is generally available now.

TABLE I
Maximum Power Ratings at 25°C

Microseal Diode	
Microseal with ribbon leads	150 mw
Microseal inserted in glass epoxy circuit board	500 mw
Microseal mounted in infinite heat sink	1000 mw
Microseal Transistor (in free air)	250 mw
Resistors	
0.050-in. diameter	$\frac{1}{10}$ w
0.100-in. diameter	$\frac{1}{8}$ w
0.125-in. diameter	$\frac{1}{5}$ w

Circuit Board Materials

Materials which have been used in the course of this study as substrate materials for the Swiss Cheese circuits are the phenolics, glass epoxy, photoceram, and also hard anodized aluminum. Each of these materials has a particular advantage. For example, the phenolics are extremely cheap, and hard anodized aluminum has the faculty for conducting heat.

Assembly Techniques

The placement of devices within a circuit card can be accomplished by at least three methods. These are (1) press fitting, a technique to which some of the circuit card materials are suitable; (2) placing the part in a loose-fitting hole and attaching it mechanically to the circuit card by use of a nonconducting epoxy, functioning as a glue; and (3) holding the parts in place using a thermal-setting sheet epoxy.

TABLE II
Available Pellet Components

Device	Typical dimensions		Range of values	Price range for quantities of 1000 units
	Diameter in.	Thickness in.		
Microseal transistor	0.080	0.030	npn and pnp planar and mesa diffused	\$1.00–\$15.00
Microseal diode	0.062	0.030	Zeners and planar diffused	\$0.50–\$5.00
Resistor	0.050	0.030	50 ohms to 1 megohm	\$0.60–\$1.00
Capacitor	0.100	0.030	5 pf to 0.001 mf	\$0.60–\$1.00

At Hughes, we have worked with at least six different schemes for intraconnecting the devices within the single-circuit module. These are (1) welding (which includes ultrasonic welding); (2) dip-soldering; (3) screen-printing a conductive adhesive from the device to a printed circuit pattern; (4) electric and electroless plating; (5) screen-printing the entire circuit pattern without benefit of a printed circuit wiring pattern; and finally (6) our new so-called decal method. The two techniques which appear most suitable at this time are the dip-soldering technique, which is rather straightforward and the decal method.

The Decal Method

Figure 5 shows decals which have been made by stenciling of a conductive adhesive ink for a particular wiring pattern to be produced on a Swiss Cheese module, A side and B side.

Using the decal technique, a blank Swiss Cheese circuit card is used, without benefit of any wiring patterns. The devices are loaded within the proper holes, and the decals placed above and below the circuit with the wiring patterns inward. Under heat and pressure, the decal material and ink are secured to the circuit module, accomplishing both mechanical and electrical connections simultaneously.

Using this technique, provisions for interconnections can be accomplished at

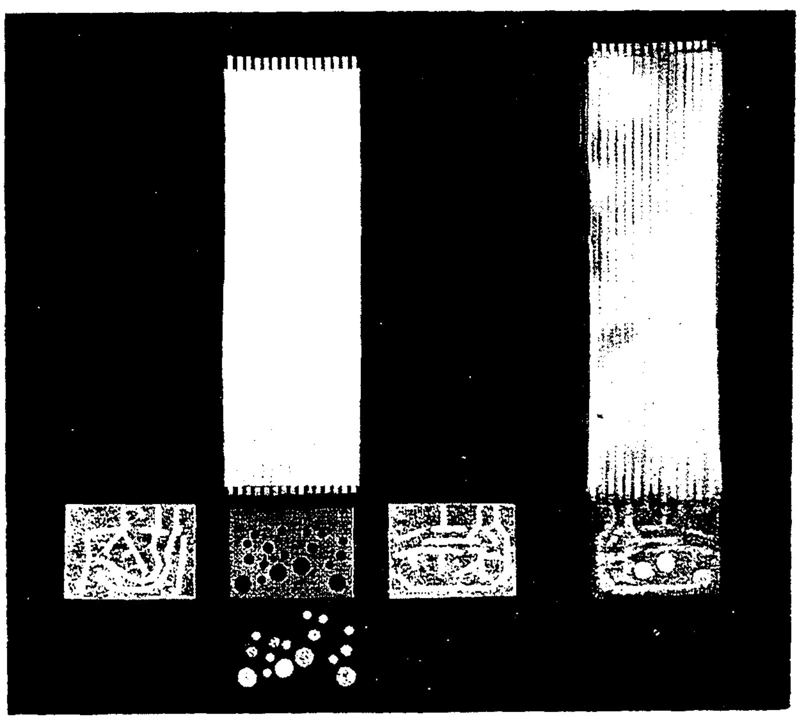

Fig. 5. Decal assembly method.

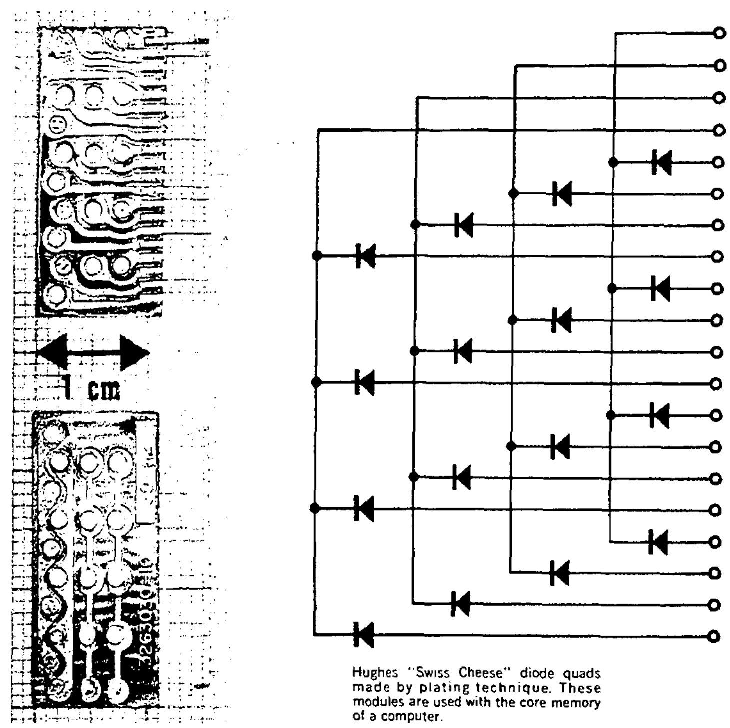

Fig. 6. Diode network.

the same time. That is, Hughes Contour Cable* can be included in the sandwich and is then mechanically held and electrically continuous with the wiring pattern of the decal. Pins can be included in the sandwich, or standard printed circuit board edge connections used for plug in. These, then, constitute three means for interconnecting modules that we have studied at Hughes: pins, the Hughes contour cable arrangement, and standard printed circuit board plug in (Fig. 6).

Operating Circuit Models

Some of the circuit modules which we have actually fabricated and operated at Hughes are shown in Figs. 6, 7, 8, 9 and 10. They illustrate not only the different inter- and intraconnection schemes, but the broad range of capability of this technique to reach linear as well as digital circuits.

ADVANTAGES AND DISADVANTAGES OF SWISS CHEESE

The principal advantages of the Swiss Cheese technique are: its simplicity; the fact that it is repairable; the flexibility, as illustrated by the various means available

*Trademark, Hughes Aircraft Company.

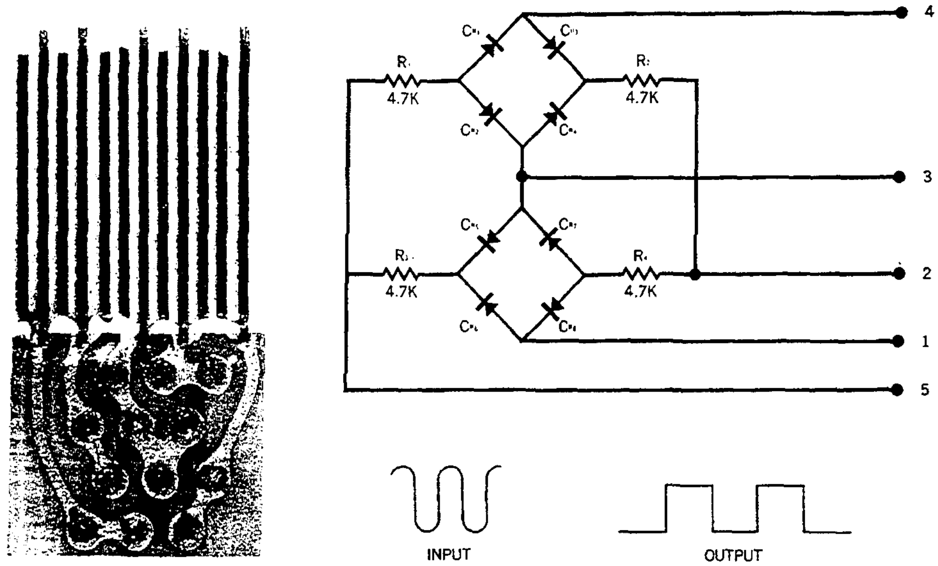

Fig. 7. Microelectronic rectifier network demodulator.

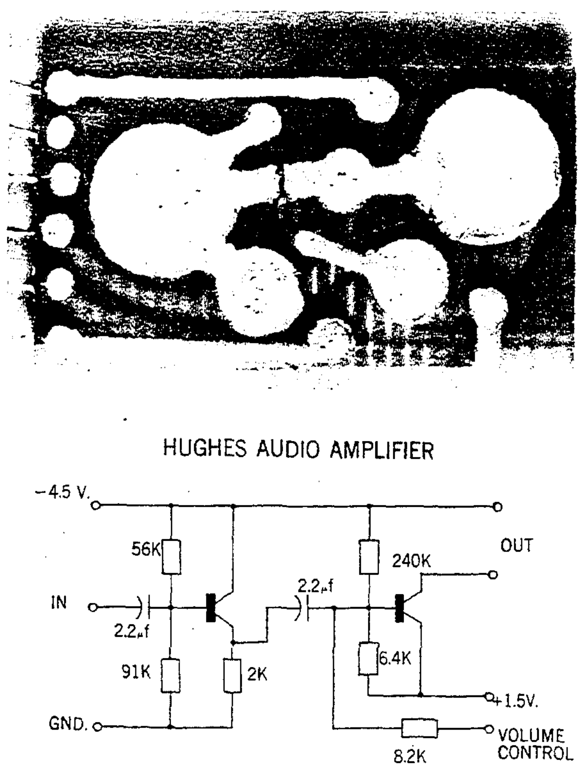

Fig. 8. Hughes audio amplifier.

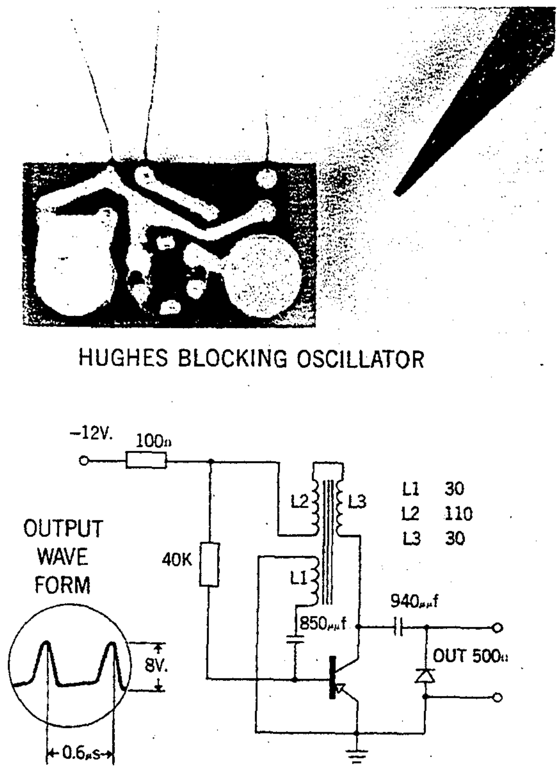

Fig. 9. Hughes blocking oscillator.

for intraconnecting and interconnecting; the range of substrates; the ease with which it can be assembled; the fact that last-minute design changes are easily implemented; the ease of intraconnections; the fact that interconnections are minimal; and the high susceptibility of this technique to mechanical assembly.

Because a Swiss Cheese module is repairable, we can consider large circuit cards. The more components put on a single card, the easier the interconnection problem with a given system.

An additional advantage which will surprise many followers of microcircuit techniques is the power dissipation which can be realized with Swiss Cheese. Devices are designed for low thermal resistance and arranged so that all devices are equidistant from cold-plate-type heat sinks. A square inch of circuitry in glass epoxy was run at 10.2 w for nearly an hour and the temperature rose to just under 60°C, while the temperature difference from board to heat sink never exceeded 5°C.

While not all values of components are available and proven at this time, the demand occasioned by increased interest in this technique is broadening circuit design potential.

CONCLUSIONS

The broad range of application of the Hughes Microseal diodes and transistors is shown in Fig. 11, from the small welded modules 13A, of course Swiss Cheese

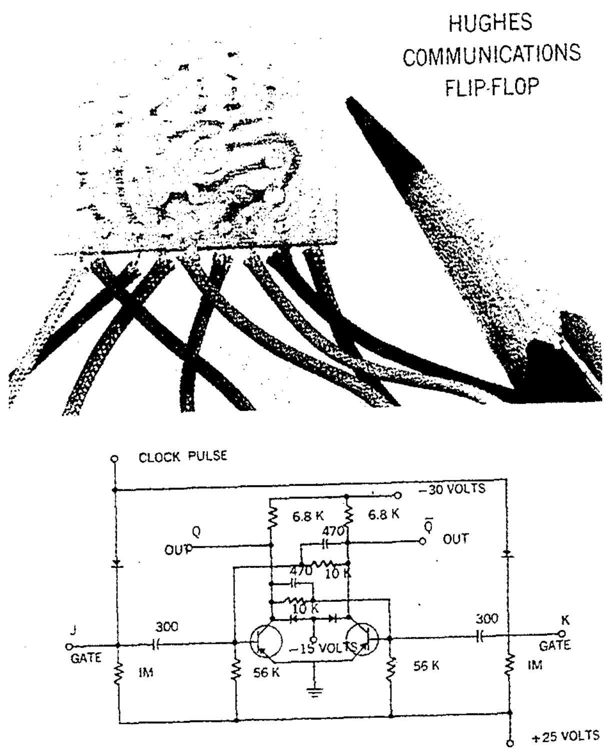

Fig. 10. Hughes communications flip-flop.

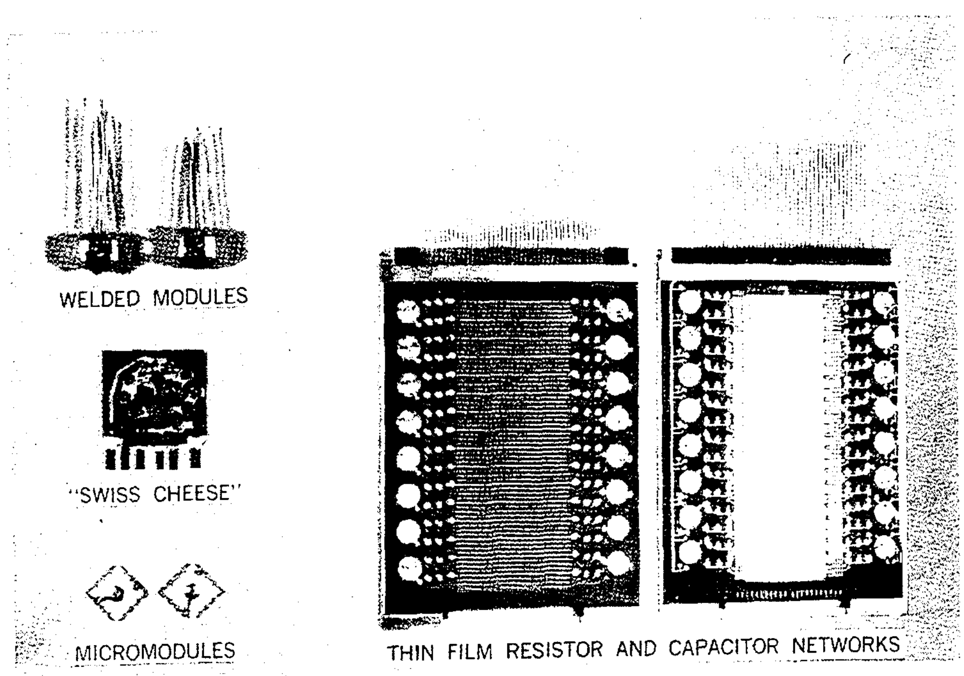

Fig. 11. Application range—microseal devices.

13B, the Signal Corps micromodule program 13C, to use with thin-film *RC* networks 13D.

The quality, availability, and range of passive and active components and module assembly techniques developed to date show that development of the Swiss Cheese circuit technique is at a point where it is reasonable to begin planning on systems fabrication programs.

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Electronic Networks from Pellets

C. HUETTEN AND L. P. SWEANY

P. R. Mallory & Co. Inc., Indianapolis, Indiana

Pelletized electronic elements are simple, small, and producible, and they are well on their way to being proven reliable and low in cost. This paper describes several basic pellet arrangements and techniques for making interconnections to form electronic networks. Stress is placed on a uniform element size and simple universal connectors leading to high flexibility of design and production with short lead times and low costs. A microcircuit module packaging system which permits high component density and smaller equipment is discussed.

INTRODUCTION

THE CONCEPT of pelletized electronic circuit elements rapidly is gaining recognition as a means of achieving economical size reduction in electronic assemblies. The tiny pellets, resistors, capacitors, transistors, and diodes are simple in shape and producible, and they are well on their way to being proven reliable and low in cost. Leadless pellet circuit elements are particularly adaptable to automatic handling techniques in preassembly testing, and in assembling groups of elements into microcircuits.

While the pellet is an ideal shape for the single-circuit element, the rectangular parallelepiped is an ideal shape for an assembly of circuit elements. With terminals emerging from one face of the module for convenient assembly, and with module sizes systematically controlled to provide good fits, the objective of smaller equipments is attainable. An approach to obtaining good fits among modules, called the "Binary Modular Dimension System" will be described.

Although pellets may be assembled in a number of ways, we shall deal with a natural evolution of simple to complex pellet assemblies, while preserving the concepts of simplicity, small size, producibility, and potential for reliability and low cost.

THE SINGLE-PELLET ASSEMBLY

Let us first consider the termination of a single pellet which will illustrate the basic terminal design parameters and the techniques of terminal assembly. The size of the pellet circuit elements to be used in all of the terminating and assembly methods to be described is $\frac{1}{10}$ in. in diameter by $\frac{1}{16}$ in. thick. These dimensions have been established in consideration of:

1. The economics of producibility
2. Adaptability to hand and automatic assembly
3. Element ratings and performance
4. Interconnection techniques
5. Assembly terminations

With our basic concept of terminals emerging from one face of a module, the single-pellet assembly must have the same feature. Figure 1a shows a pellet and its terminals prior to assembly and Fig. 1b shows the terminals assembled to the pellet. To obtain a center-to-center terminal spacing conforming to an acceptable grid system, the terminal material thickness is made 0.012 in. When these terminals are assembled to the $\frac{1}{16}$-in. pellet, the spacing is 0.075 in., which conforms to the widely accepted 0.025-in. grid system. The two legs on the "A" type terminal have the same center-to-center spacing. The square ends of the terminals permit simple fixturing for accurate location on the pellets during assembly and the hole provides space for excess solder when the assembly is made by soldering. The "A" terminal is standard for one terminal of all single-pellet elements and is used for polarity identification where required.

These flat terminals have several fundamental advantages. They are economical to fabricate, and individual handling is eliminated by leaving the terminals

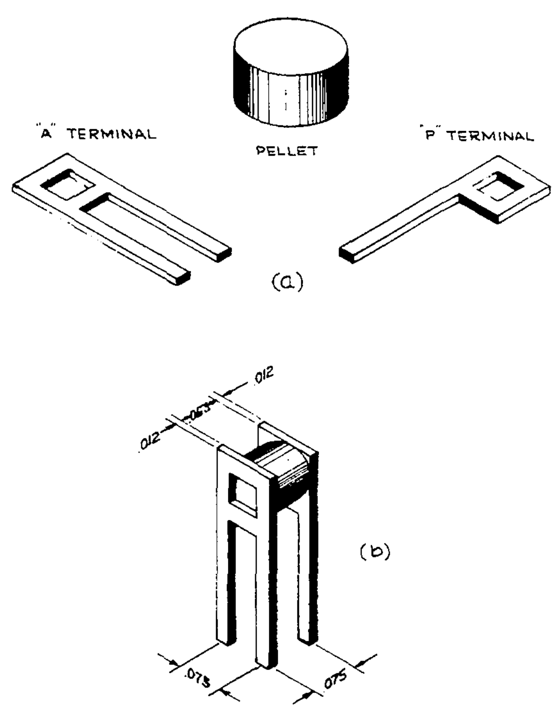


Fig. 1. Terminals for single pellets.

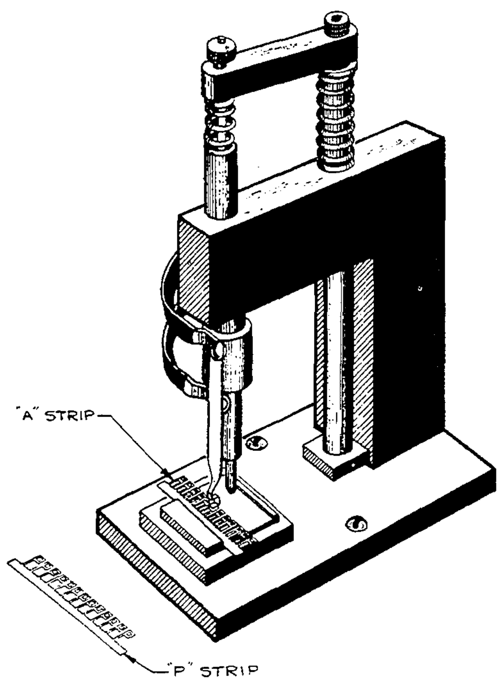


Fig. 2. Multiple assembly of terminals by resistance-soldering.

in strip form for multiple assembly. The flat terminal presents a relatively large area to the pellet face, and by using copper material intimately bonded to the pellet by soldering, a low-thermal-resistance path is obtained for removal of heat from the pellet.

Figure 2 illustrates a manually operated resistance-soldering press for

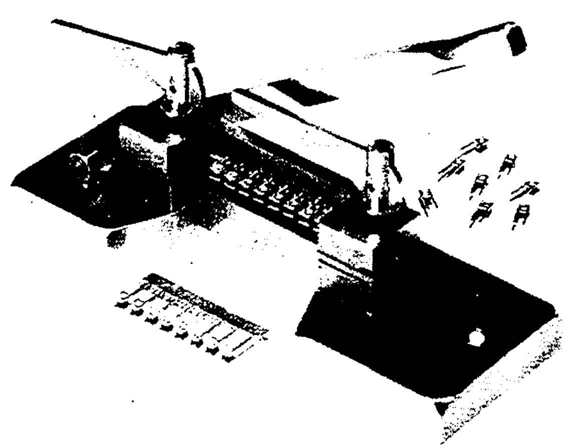


Fig. 3. Terminal shear.

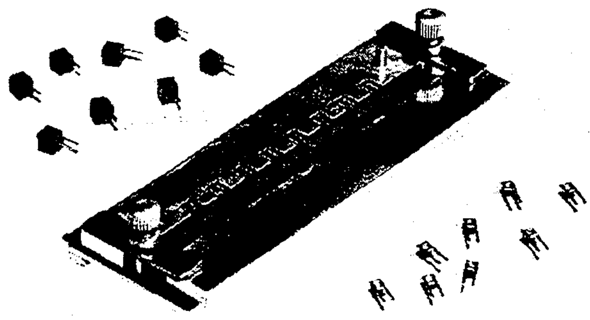


Fig. 4. Laboratory encapsulation mold for single pellets.

assembling terminals to pellets. The terminal material is solder-coated copper, and no additional solder is required to make the bond. The pellets are positioned on 0.150-in. centers in a nest, and a strip of "A" terminals is located on the pellet faces. Upon actuating the press, a carbon electrode contacts the terminal over the pellet and a spring contactor presses against the terminal tie strip. A timed electrical pulse applied to this circuit heats the terminal at the carbon electrode causing the solder to flow. A "hold time" in the soldering head allows the joint to cool before the electrode is lifted from the work. The partial assembly is then removed from the nest and turned over to receive a strip of "P" terminals, which are attached in the same manner. The parts are then cut loose from the tie strip using a floating plate shear that clamps the terminals so that shearing stresses are not transmitted to the pellet faces. Figure 3 shows the terminal cutting operation. Final encapsulation in an epoxy resin for mechanical and climatic protection is done in a multiple cavity mold as shown in Fig. 4. The single-pellet components are molded into a 0.150-in. cube, which becomes the basic modular dimension for other packages.

MULTIPLE-PELLET INTERCONNECTIONS

In visualizing how one physically might arrange a group of pellets which could be connected to form a circuit, five distinct possibilities will be discussed. With reference to Fig. 5, a series of pellets has been arranged on the rectangular coordinate axes X, Y, and Z. It is evident that pellets may be arranged in a single row along each of the axes to form relatively simple circuits (the Y axis being redundant in this case); or that two-dimensional arrays may be formed by combining the X and Y axes, or the X and Z axes; or that a three-dimensional array of pellets may be formed utilizing all three axes. For the purpose of identification in the following text, we shall use the XYZ coordinate letters to indicate the pellet arrangement in a particular package style. Thus we will have an X-pack for pellets arranged on the X axis; a Z-pack for pellets arranged on the Z axis, an XY-pack for pellets arranged in the XY plane, an XZ-pack for pellets arranged in the XZ plane, and

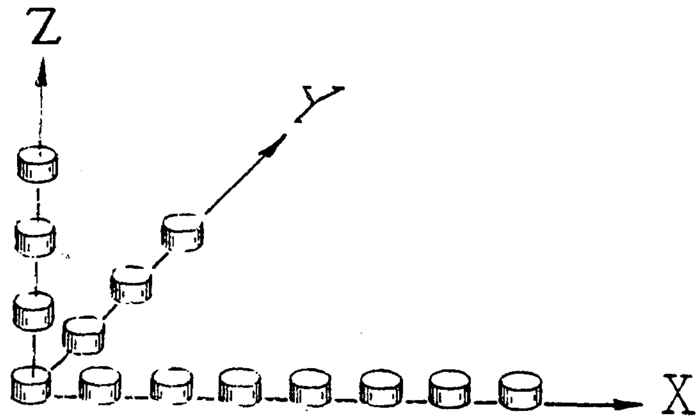


Fig. 5. *XYZ* pellet arrangements.

finally, an XYZ-pack for the three-dimensional pellet arrangement. Let us first consider the two simple pellet arrangements and the circuits to which they are applicable.

The X-Pack

The single-row, side-by-side arrangement of pellets is applicable to circuits requiring parallel connected components or components having one terminal common. One application is the resistor network used in transistor collector supply circuits. Figure 6 illustrates a "ladder" connector strip and its use for connecting a

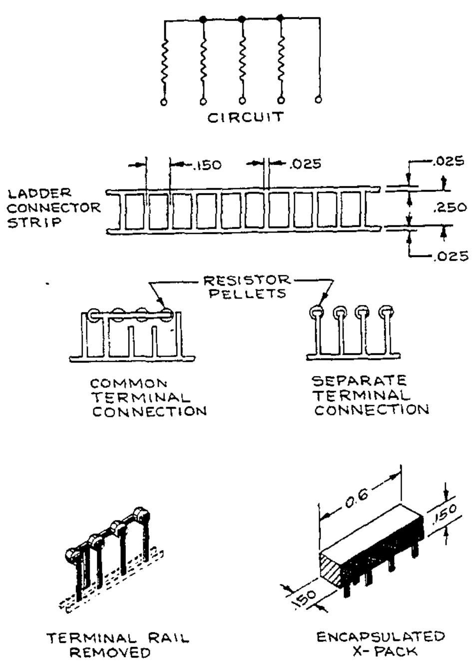


Fig. 6. Common terminal network using ladder connector strip.

simple four-pellet resistor network. (The same technique is applicable to any combination of resistors, capacitors, and/or diodes.) One side rail and the rungs of the ladder are the conductors. By removing certain portions of the ladder, the same strip may be used for making and terminating the common connection to the pellets, and also for terminating the separate connections to the pellets. The strip is solder-coated copper for bonding to the pellets by means of resistance-soldering. The rungs of the ladder are on 0.150-in. centers so that the terminals will fall on a 0.025 grid. With reference to the illustration, the common side of the circuit is prepared by removing all but one of the rungs from a portion of the ladder strip. The four pellets are nested in a row on 0.150-in. centers, after which the common connector is centered on the pellets and resistance-soldered. Location of the common terminal is optional, but it should fall between two pellets so as to give maximum space for making connections to the terminal. The subassembly is turned over to expose the opposite terminal faces of the pellets. Small sections of the upper rail are removed from a length of ladder strip so that the rungs may be used as separate resistor terminals. The row of rungs are then centered on the pellet terminal faces and resistance-soldered. The lower tie rail on both circuit halves is separated from the assembly using the same shear described for the single-pellet assembly. The circuit is now ready for cleaning, testing, and encapsulation.

The encapsulated size of this simple network is $0.150 \times 0.150 \times 0.600$ in., the length being a multiple of the 0.150 modular size. The ladder connector strip offers a means of universal connections for a group of simple networks, and it fulfills the need for producing new circuits rapidly without complex tooling. Circuit changes may be made with negligible cost penalty.

The yield of pellet assemblies is high, because all circuit elements may be pretested before assembly. Changes in element values caused by design changes quickly may be made without appreciable down-time during a production run.

The *XY*-Pack

Arranging the pellets in the *XY* plane is a natural expansion of the simple *X*-pack. More components may be used in a single package without excessive length, and more complex pellet interconnections may conveniently be made within the module. Pellet interconnections for the *XY*-pack are made with a Universal Connector Strip (UCS) consisting of a die-cut grid of 0.012-in. copper having 0.025-in. wide conductors on 0.075-in. centers, both horizontally and vertically. Terminals integral with the grid also are on 0.075-in. centers. A section of this strip is shown in Fig. 7. Note how it has been expanded from the "A" terminal strip used for terminating a single pellet.

By placing the pellet components on 0.150-in. centers and at the junction of a horizontal and vertical conductor, connections to the pellet may be made from four coplanar directions. The conductors on the 0.075-in. spacing between the pellets are used for routing the circuit. This permits considerable flexibility in circuit layout and component location. Once the circuit routing has been established, the unwanted conductors are removed from the grid, and the connector strip is ready for assembly to the pellets. The 0.150-in. matrix for assembling 0.100-in. pellets

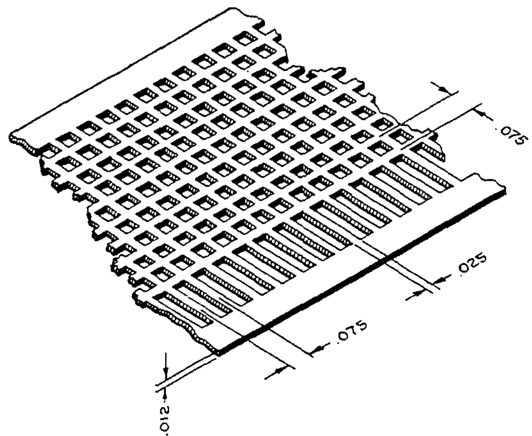


Fig. 7. Universal connector strip.

in the XY arrangement permits an alternate pellet diameter to be used for micro-components requiring greater volume. A 0.25-in. diameter pellet, which will occupy the space of four 0.100-in. diameter pellets, may be introduced into the matrix without affecting the advantages of the concept.

XY-Pack Circuits

At the present time, a generalized approach is being used in locating the pellet components for the XY-pack. For illustration, assume that we have a parallel-tee network containing twelve components which we wish to translate into an XY-pack layout. With full freedom in selecting the height and length of the finished package, we have six choices of pellet arrangements:

Choice	*No. Pellets High*	*No. Pellets Long*
1	1	12
2	2	6
3	3	4
4	4	3
5	6	2
6	12	1

Choices 5 and 6 are obviously poor for mechanical reasons, and numbers 1 and 2 may not provide enough conductors on the connector strip to obtain the desired circuit. Choices 3 and 4 appear the most appropriate, with No. 3 the better because of the availability of more terminal space. It also is a better design from the standpoint of surviving shock and vibration when connected in an assembly with other modules.

We now face the problem of locating the individual pellet components within this framework so that the circuit may be routed and the terminals brought out

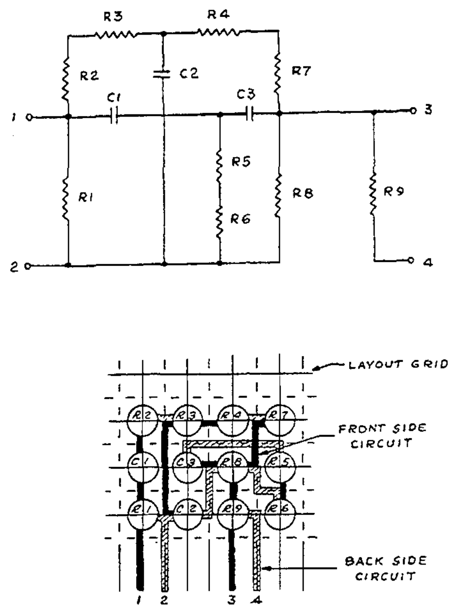


Fig. 8. Parallel-tee circuit and *XY* pellet interconnections.

without interference. The number of possible location combinations for 12 pellets is 12 factorial, or 47,900,160. Needless to say, we can eliminate about 47,900,158 of these combinations by careful circuit inspection and by logical grouping of circuit elements.

A four-to-one-scale work sheet with alternatively solid and dotted grid lines is used to make the pictorial layout of the circuit. Circles representing the 0.100-in. diameter components are placed with centers on the intersections of the solid grid lines. The dotted grid lines represent the available circuit paths between the pellets. The front and back circuit routes must be identified clearly, since the completed circuit must include connections to both sides of the pellets. For a circuit translation layout, this may be done by using black lines for the front side and red lines for the back side so that the complete circuit may be generated on one pellet array. Developing the circuit in this manner is much easier than attempting to visualize the front and back separately. Figure 8 shows the *XY* pellet arrangement and circuit routing developed from the schematic. Each component is identified by its schematic symbol as it is connected.

Conductor Path Identification

To identify the conductor paths that must remain in the grid of the Universal Connector Strip, it is convenient first to make separate drawings of each half of the circuit. A four-to-one-scale of the UCS grid printed on vellum is used for this purpose. The vellum is used as an overlay on the pictorial layout, and the conductors required for the front or "black" side are shaded in on the vellum. The vellum then is shifted, and the conductors required for the back or "red" side are shaded in. Island tie points are located, if required to prevent dropout of interconnections, and the circuits are ready for fabrication.

Note that the second horizontal conductor of the UCS is located over the centers of the bottom row of pellets. The first horizontal conductor is left free for additional circuit routing or for shifting terminals by one space to maintain a staggered 0.075-in. terminal arrangement. Figure 9 shows the UCS patterns required for the twin-tee circuit.

For development or prototype circuits where the unwanted portions of the grid are to be removed by a hand operation, visual identification of the remaining grid lines on the strip is necessary. Applying india ink directly to the strip following the vellums previously made is a convenient method for making a small number of circuits. Removal of the unwanted portions of the grid then is accomplished by using a "ticket punch" which locates in the grid holes and nips out the connecting links as shown in Fig. 10.

One of the major advantages of the UCS is its adaptability to short production runs of many circuit types. By number and letter identification of each line and junction of the UCS grid, a circuit may be transferred directly to a programmed punch which may be set up automatically or manually. A circuit change merely affects the punch program, and lead times for new circuits are greatly reduced.

Assembly of the circuit halves prepared from the UCS to the pellets is accomplished by nesting the pellets on 0.150-in. centers in their proper location, as determined from the pictorial layout. One half of the circuit is located on the pellet centers, and electrical connections made by resistance-soldering or by conductive cement where soldering temperatures are prohibitive. The subassembly is then removed from the nest, turned over, and refixtured to attach the other half of the

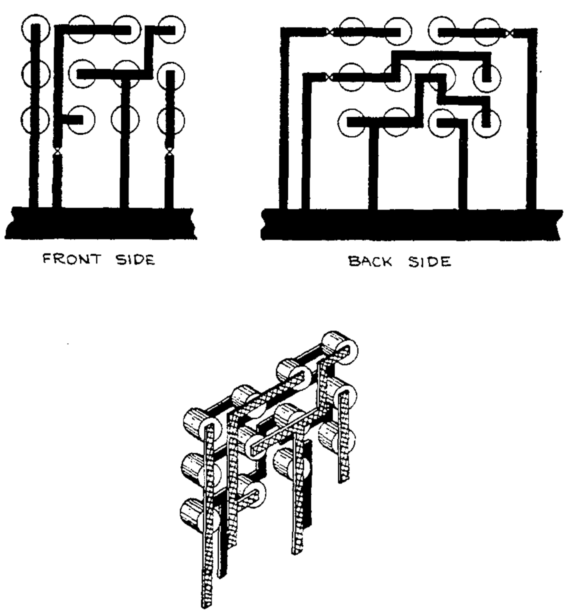


Fig. 9. Universal connector strip circuits for parallel-tee network and pellet assembly.

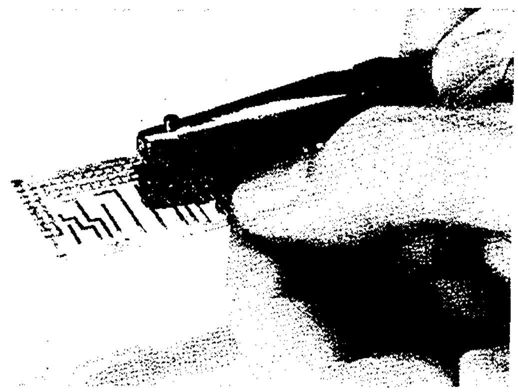


Fig. 10. Removal of unwanted portions of UCS with "Ticket Punch."

circuit in a similar manner. Island tie strips are nipped where required, and the terminals are cut free from the lower rail of the UCS using the floating clamp shear previously described. The assembly is then ready for cleaning, testing, and encapsulation.

The XY-pellet pack offers the same thermal advantages as the X-pack, because the pellet interconnection structure has low thermal resistance and is integral with the terminals. The function of the terminals for physical support in shock and vibration is more important in this package type, where appreciable height has been added. In general, most circuits of this type will have several terminals extending from both the front and back portions of the UCS. The parallel-tee assembly has two terminals on each side, which are separated by the 0.063-in. pellet thickness. This terminal separation has an advantage over in-line terminal arrangements in that it gives good support to the assembly when soldered to a printed circuit board.

This package type also is compatible with pellets other than 0.1-in. diameter, or even with pellets having other shapes as long as the $\frac{1}{16}$-in. dimension is maintained. In addition, the XY pellet arrangement is adaptable to direct assembly to an appropriate substrate where the ultimate is desired in in-process mechanical rigidity and improved heat distribution. Low-thermal-resistance materials, such as beryllia, could be extended beyond the package boundaries for connection to a heat sink.

The Z-Pack

A single-row, end-to-end arrangement of pellets is applicable to circuits requiring series-connected components. Many elements in a circuit, such as an amplifier or a flip-flop, are found to be in series, and groups of these elements may be packaged and interconnected to form modules. Figure 11 shows an assembly of seven series-connected resistors used as a voltage-divider network. The terminals in this assembly are the same as those used for the single pellet. The "A" terminal at one end of the assembly provides orientation or keying of the module to prevent improper connections. The "P" terminals are alternated down the series string to obtain a staggered 0.075-in. spacing.

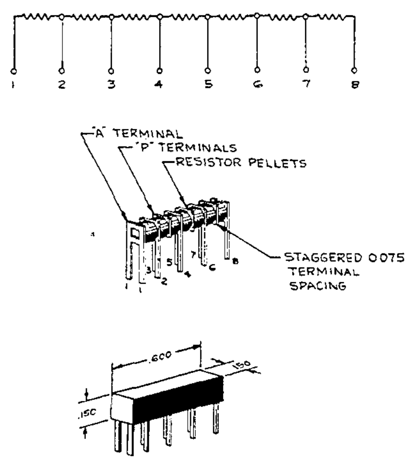


Fig. 11. Z-pack pellet assembly.

These assemblies are made in a channel nest, either singularly or in groups. The groups are formed by leaving the terminals tied to a base strip. Bonding of the solder-coated terminals to the pellet faces is accomplished by applying pressure to one end of the assembly while heating the terminals to melt the solder.

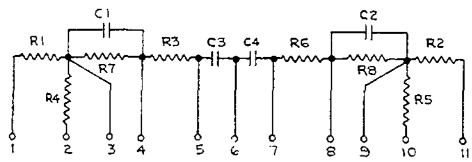
When encapsulated, this seven-pellet assembly has the dimensions 0.150 × 0.150 × 0.600 in., which is the same size as the four-pellet X-pack. With full utilization, the Z-pack will hold 75% more components for the same size as the X-pack. An insulator having the same size as a pellet may be used in the series string to isolate two separate circuits in the same package, with little resultant reduction in component density.

The XZ-Pack

The XZ-pack is a combination of the simple side-by-side and end-to-end pellet arrangement. Assemblies of this type are appropriate where several parallel elements appear in a circuit that basically is a series circuit. The major advantages of this arrangement are that a single package may be used instead of several simpler packages and the number of external interconnections is reduced. Figure 12 illustrates an RC network commonly found in flip-flop circuits, together with the pictorial layout of a two-row, seven-pellet-long XZ-pack developed from the circuit.

The terminals used for this assembly essentially are the same as those used for the Z-pack, except that a tie link is retained between the "A" terminals on the strip. This tie link provides the crossover between pellet rows, and permits convenient paralleling of elements where required. The link is nipped out prior to assembly if it is not required in the electrical circuit. The assembly process for this pellet arrangement is similar to that used for the simple Z-pack assembly.

In the pictorial layout, the pellet stacks are shown separated further than normal so that the terminals may be seen. The axial spacing of stacks is 0.150 in. The pellets marked with "I" are phenolic or ceramic insulators with metallized ends. These are soldered in the same manner as the rest of the components to



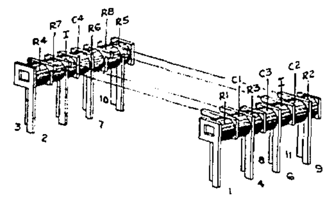


Fig. 12. *XZ*-pack pellet assembly.

make a rigid assembly. When encapsulated, this assembly is 0.150 in. high by 0.300 in. wide by 0.600 in. long.

The *XYZ*-Pack

An arrangement of pellets combining all three of the coordinate planes as shown in Fig. 13 represents the ultimate in high pellet packaging density. Although no circuits have yet been developed in this configuration, nor have interconnection techniques fully been worked out, the concept is challenging. With the same pellet spacing as previously described for the *XY* plane, a 1-in.^{3} *XYZ*-pack has 504 pellet positions. It is apparent that some number of pellet positions must be occupied by insulators so that adjacent levels in the *XY* plane may be isolated. Also, shielding planes may be required to separate circuit sections. With a component, use factor of 75%, the actual density would be 375 elements/in.^{3}, or more than 600,000 elements/ft^3.

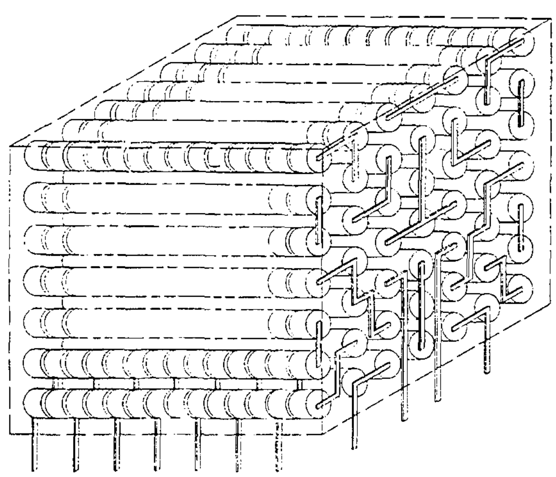


Fig. 13. *XYZ*-pellet assembly.

PELLET MODULES

It was stated earlier that:

1. An ideal shape for an assembly of circuit elements or a module is a rectangular parallelepiped.
2. All terminals should emerge from one face of the module for convenient assembly.
3. The module sizes should conform to a dimensioning system that results in good fits among modules.

The first two factors have been discussed in the preceding paragraphs. Several illustrative packaging arrangements have been described. A solution to the third factor is found in what we call the Binary Modular Dimension System. In this system, module heights, lengths, and widths are fixed at 1, 2, 4, 8, etc., times the basic modular dimension. In any one height category, it can be shown that good fits and high module density may be obtained from a random selection of a number of modules following the binary system on length and width dimensions.

For pellet component assemblies, we have chosen 0.150 in. as the modular dimension. Table I gives the width and length of pellet modules in 0.150-, 0.300-, 0.600-, and 1.2-in. module heights.

TABLE I

Width	Length
0.150	0.150
0.150	0.300
0.150	0.600
0.150	1.200
0.300	0.300
0.300	0.600
0.300	1.200
0.600	0.600
0.600	1.200
1.200	1.200

The maximum number of pellets in each modular length of the X- and Z-packs is given in Table II. Module height and width in each case is 0.150 in.

TABLE II

No. of Pellets	Package Style	Length
2	X	0.300
4	X	0.600
8	X	1.200
4	Z	0.300
7	Z	0.600
15	Z	1.200

The maximum number of pellets in each modular size of the XY-pack is given in Table III. The thickness of these modules is 0.150 in.

TABLE III

No. of Pellets	Height, in.	Length, in.
4	0.300	0.300
8	0.300	0.600
16	0.300	1.200
16	0.600	0.600
32	0.600	1.200
64	1.200	1.200

The maximum number of pellets in modular sizes of the XZ-pack is given in Table IV. The height of each of these modules is 0.150 in.

TABLE IV

No. of Pellets	Length, in.	Width, in.
8	0.300	0.300
14	0.300	0.600
30	0.300	1.200
28	0.600	0.600
60	0.600	1.200
120	1.200	1.200

MODULE ENVIRONMENTAL PROTECTION

The pellet assemblies we have described are adaptable to mold casting as well as potting in an insulating shell. Thin-wall epoxy shells which recently have become available are particularly suitable for high production quantities of modules. These thin-wall shells permit the maximum use of internal space while at the same time permitting full control of the external modular dimensions.

For low production rates, the casting technique appears to be the most economical. Figure 4 illustrates a simple laboratory molding fixture that permits several pellet assemblies to be molded simultaneously. The basic parts of the mold are the base plate, rubber terminal seal, and cavity sections.

The degree of protection afforded by the molding process is dependent upon the continuity of the cast surface and the material used. A good casting will have no surface flaws or pin holes. We currently are using Isochemrez Epoxy No. 114D with Hardener #6. This material provides a module having good mechanical and thermal properties and a low rate of moisture absorption. Hardener #6 permits curing at temperatures compatible with germanium semiconductor devices where required. It also permits faster curing at higher temperatures if this is desired.

MODULE RELIABILITY

A number of developmental packages have been fabricated using the several pellet arrangements and soldered assembly techniques described. Many of these packages have been subjected to environmental extremes and some have been placed on elevated temperature load life. Test results to date indicate the capability of attaining a high degree of reliability. From the interconnection standpoint, no failures have been noted in over 400,000 interconnection-hours.

Reliable soldered connections will be maintained in production by close control of the soldering operation and by visual inspection for bright-line filleting of the solder between the terminal and the pellet face.

In addition to thermal and mechanical reliability factors inherent in the package designs, overall module reliability will be achieved through strict control of all fabrication processes and materials and in-line inspections. Plans are underway to demonstrate module reliability by large-scale testing and statistical analysis by the Microcomponents Department Reliability Section.

CONCLUSION

To a great extent, the economical attainment of smaller equipment is dependent upon the adaptability of the parts of the equipment to be mechanically handled and assembled. Although we have not discussed specific methods and techniques for automatic pellet handling, it is apparent that this simple form is most adaptable to mechanization. Potential reductions in lead times and costs associated with circuit changes as compared to the printed circuit approach has been demonstrated by the actual use of Universal Connector Strips. The performance of modules as they would be fabricated in production may be quickly determined by preparing breadboard and prototype circuits from production materials with simple hand tools. Component value changes, which can be costly in time and money in many microcircuit approaches, may be made immediately during the pellet assembly operation.

These factors, coupled with appreciable size reduction over conventional component assemblies, and the potential for high-reliability, low cost pellet microcomponents, make pellet assemblies attractive for microcircuit applications.

DISCUSSION

Q. (Leonard Marks, General Dynamics/Astronautics, San Diego, Calif.) (To the gentlemen from Mallory) I noticed that in none of your sample circuits do you show active elements. Is there any significance in this?

A. I didn't get the first part of your question.

Q. I said I noticed that in none of your example circuits in the preprints or on the slides do you show active components, semiconductor components. Is there any significance in this?

A. There is one significance, yes. There is only one company currently producing anything in our particular pellet size, $\frac{1}{10}$ in. in diameter by $\frac{1}{16}$ thick. And rather than spoil the uniformity of the system by introducing odd sizes, semiconductor elements were not included. Many of our circuits are adaptable to hybrid, but I wanted to demonstrate the advantages of the uniform pellet size. Controls Co. of America does produce some diodes and I understand has at least one transistor available in the $\frac{1}{10}$-in. size.

Q. There is no technical problem?

A. As far as I see at this time, no. We have actually used some of Mr. Bender's microseal transistors in a demonstration package but it was a flip-flop and I didn't think we ought to repeat this classical example.

Q. I have another question for the gentlemen from Hughes. You mentioned repairability. Could you be a little more detailed about repairing, say, your decal method of interconnection?

A. You have chosen the most sensitive one. That is the toughest one to repair. You must, of course, identify the component which is offending and then, by grinding, remove the portion of the decal covering the device. It may then be punched out. A new component is then inserted using an epoxy functioning as a glue. Then a conductive adhesive is used to join the replacement to the original wiring pattern. The plating technique, the dip-soldering technique, and the conductive adhesive method are much more easily subject to repair.

Q. (Al Acken, RCA, Van Nuys, Calif.) I would like to know if you have ever had any success in one of the diodes with a hand-soldering iron?

A. In preparing Microseal devices for life tests, this is a common practice. We use a single-holed Swiss Cheese circuit card that is about $\frac{1}{2}$ in. long and $\frac{3}{8}$ in. wide with the appropriate wiring runs. The device is mounted to the card by hand-soldering. It works out quite well as long as you don't use too hot an iron, and work quickly.

Q. (Lyle Robinson, Bendix Corp., Kansas City, Mo.) I had a question for Mr. Bender. About the reliability of the electrical connection used in the adhesive epoxy. Are you sure that you are getting a good reliable joint, since you are not soldering or welding?

A. We have perhaps 8 or 10 years of experience with the DuPont No. 5780 thermosetting gold. This material has been used in glass diodes for this number of years to mount the semiconductor chip to the wire inside the standard glass package. We have made and sold millions of devices fabricated by this technique and they have been MIL qualified. They have passed all the hells that are required of them. We have a high degree of confidence in this material. Also Hughes has used various conductive silvers in the Falcon missile for shielding in conduction for perhaps five years.

Q. I also had a question for Mr. Sweany. On your *Z* arrangement, I was interested in how you managed to solder the terminals between two adjacent pellets? The other was rather straightforward but I couldn't really see how you could physically accomplish this the way you have the pellets stacked.

A. It probably isn't nearly as clear as the other method, but in this assembly technique we stack the pellets and terminals alternately in a channel, the terminals being lightly fluxed. In our present laboratory method we apply heat to the end of the terminals with a controlled-temperature soldering iron, and at the same time apply pressure to the end of the stack. We have other plans for better methods of doing this than by hand.

Q. (Walter Weick, Bell Telephone Labs., Whippany, N.J.) I would like to address my question to the man from Mallory. On the resistance soldering, if you are doing this on a 12-mil-thick copper strip what sort of current cycle do you need in order to resist the heat?

A. What sort of what, sir?

Q. Current cycle in order to get your heating?

A. Well, in this case we had originally used the conventional power supplies, supplied with the resistance soldering hand fixtures. But, recently, we have found that a capacitance discharge through this electrode circuit gives a short pulse which is less detrimental to the components. We are using between 70 and 100 w-sec from a capacitance discharge welder power supply for the various types of components. So I can't give you a real figure on the current or time, but in watt seconds, that is about what we are using.

Q. (Don Schnorr, RCA, Camden, N.J.) I have a question for Mr. Bender. He mentioned that when they first started making the substrate they investigated hard anodized aluminum. Was this in effect to cut down crosstalk between high-speed circuits?

A. Our principal interest here was in thermal conduction. We had heard a good deal about beryllia having the equivalent thermal conductivity of aluminum. This led us to try aluminum itself. With a hard anodized coating 2 mils thick, sufficient isolation of the components and the wiring from the bare metal underneath it is achieved. It works out quite well.

Q. (Al Gaetjens, General Electric, Valley Forge, Pa.) I have a question for Mr. Bender. In the interconnection method involving plating how are those pellets mechanically held in place during that operation?

A. Our present method is to use a thermal-setting epoxy functioning as a glue. This is probably a tedious process at this time. We envision eventually being able to start with uncured glass epoxy sheet stock. Fairly tight-fitting holes will receive the devices. Curing of the epoxy sheet with the devices in place will get us out of this hand-gluing business.

Q. (Bill Johns, Martin-Marietta, Baltimore, Md.) Since all components have the same form factor, what method of identification do you use?

A. Do you mean coding?

Q. No, I want a method that will tell me exactly what component I have now that I have this little pill in my hand.

A. The Hughes Microseal diodes and transistors are of different diameters. The diode is 0.0625 in. maximum whereas the transistor is 0.080 in. maximum. The transistor also has terminals on one face which are silver in color and on the opposite side resides the collector electrode which is gold in color. It is pretty easy to tell whether you have a transistor diode, once you are used to seeing them.

Q. I was basically interested in the resistors and the resistor values?

A. I will let Mr. Huetten answer that question. Generally, we do not attempt to identify each individual pellet, although we can by putting them in the card with identification. However, in our production setup we would plan on putting all resistor pellets of a particular value in one container, such as a magazine, which could be placed in a machine ready for automatic assembly. The magazines could be put into a laboratory dispensing device having a number of stations for pellet types and values. We could then assemble pellets in their proper position in a nest or a board. We stock them in groups. We identify the contents of the group in one container rather than individually.

Q. Do you mean after you take the component out of the case and it happens to be associated with other components, there is no way of identifying which component you have after it is separated from the lot?

A. It would be identified while it is in the lot. When it is separated, normally, it would be either in a magazine with like types of components, or in a laboratory dispenser of like types of components. Basically, there need be no manual handling from there on, and no reason for it to be misplaced. In the laboratory, we generally keep them in separate containers and we have a certain order of positioning in the assembly nest. We draw them from a particular container and put them in a particular hole in the nest. If you mixed them all up, then we have a machine, for example, which automatically selects resistors to value. You dump them in a vibratory feeder where they are bridged and dropped in the proper container.

Q. (Jim Wick, Centralab, Milwaukee, Wis.) I have a question for the gentleman from Mallory. On the capacitor pellets of the relatively small diameter and quite large thickness, don't you have some very serious limitations on the obtainable capacity?

A. Our ceramic capacitors are made with a very thin wafer of ceramic which is sandwiched between two nickel terminals, which are in turn gold-plated so that they can either be welded, soldered, or connected by conductive cement; again, you can choose your method of connection. The actual ceramic is a very thin disc around 8 to 10 mils thick. So we can get from about 2 pf to about 1000 pf in that size. We have an alternate size $\frac{1}{4}$ in. in diameter, which gives us up to about 4700 pf. In our XY pellet arrangement, the $\frac{1}{4}$-in. pellet occupies the space of four $\frac{1}{10}$-in. pellets.

Q. (Harvey Zaid, Nortronics, Anaheim, Calif.) Getting back to the problem of identification of resistors—aside from using an ohmmeter, it seems to me that it is conceivable that with proper automation techniques, you could color code the circumference of the dot. Is this feasible?

A. This would be feasible and very easily done in a mechanized manner. Some people, however, require a very close diameter, e.g., for press fits, and the coding paint may interfere. This could be done, I think and in small quantities it may be advisable. However, in a production environment we don't think it would be necessary.

Q. (John Rivera, RCA, Somerville, N.J.) It seems to me that if you can't identify a basic component, the handling problems are going to be pretty severe. It may very well be that in the laboratory, in your laboratory, one can control the environment, but suppose this gets expanded into a rather large production system where the networks involve many suppliers feeding in pellets. It seems to me there would be some serious problems. How would you handle this, or what about pellets that you might want to take out of a board? How can you tell what the pellet is without going to a schematic or some other very ticklish technique?

A. We could, of course, identify each pellet and we could associate it with some piece such as the card. One production method we have in mind would put pellets of a particular kind in a magazine, which defines all the pellets in that magazine. They are transported in this magazine. They are placed in the machine that would do your assembly in the same magazine and really never need be handled individually. However you said they should be also tested before they are entrusted to an assembly and machines can be readily made to take them from a magazine, check them, and put them back in the magazine. If you should have an assembly where they are not correct then you will just have to take the necessary care or maybe those units could be identified as you suggest.

Bender—I would like to add one thing. You inquired about identifying a component once it was removed from the circuit. Generally speaking, the only reason you would want to remove one was because it has failed. You would then want to throw it away.

Q. (Jake Rubin, Martin-Marietta, Baltimore, Md.) Mr. Bender, the implication that you give us is that these semiconductor devices are certainly equal to, or superior to, anything on the market electrically and performancewise. Mechanically, they seem to be rather easy to produce. Are we to assume that after a certain period of time when one cuts open a Hughes semiconductor can, he will find one of these in there?

A. Our current fabrication of Microseal devices is such that the junction that appears inside the small ceramic package is identical to the junction that would appear in a larger package. In certain of our processes, up to a point, the device on the slice, say, simply doesn't know whether it's going to be packaged as a Microseal device or a glass diode or a TO-5 transistor. So the junctions are identical. I think you have been reading our literature on the transistor. With this concept, which we are now pursuing actively in the factory, we run all of our planar diffused transistors in the Microseal package with leads. These leads will be of nickel. When a requirement comes for a device packaged in a TO-18, TO-46, or TO-5, the Microseal subunit is put into the appropriate can along with filler material. This will produce a device of identical form factor for the one required. This has a number of advantages. Have you ever had occasion to bend the leads of a standard TO-5 package, breaking away some of the glass leaving bare Kovar? This Kovar, no longer protected by glass or gold plating, will not survive salt spray tests. The salt spray will cut the leads off. The solid nickel wire, which appears as the lead material of the repackaged Microseal transistor, is not destroyed by similar salt spray testing.

Q. (Ed Cormier, General Dynamics/Astronautics, San Diego, Calif.) Question to Mr. Huetten—Have you considered drawing radial lines along the periphery of the resistor and some series of lines indicating the value of the resistor? It would clinch in the hole of a printed circuit board better.

A. I didn't understand the last part of your question.

Q. If you draw lines, serrations or lines, along the outside periphery of the resistors along the circumference, you might be able to code the value there and perhaps even assist in clinching the component into the hole drilled into printed circuitry.

A. No, we haven't thought of that. I think that probably could be done on ceramic capacitors and carbon composition resistors. However, on film resistors I think it may interfere with the film itself.

Q. (Al Gaetjens, General Electric, Valley Forge, Pa.) Could someone describe if it's possible to weld directly to the pellets and if so, how?

A. Bender—We've actually welded ribbon leads to the leadless device in response to certain customer requests. Our approach is to weld flat ribbon wires. The ribbon is placed on top of the component electrode. Both welding electrodes are brought to bear on the top surface of the ribbon about 0.030 in. apart. Using nickel or alloy 180 ribbon material of 0.003 to 0.005 in. thick causes the resistance through the ribbon to be greater than the resistance through the interface. Thus, the weld current passes through the interface, across the cap, and back out again. This is a method by which you can weld.

Other speaker—I was going to add just one bit to that. We have, not in our laboratory, but we have had samples by welding companies about pellet components welded in this fashion and it is applicable and feasible.

PANEL DISCUSSION

Welded *vs* Soldered Connections

SOLDERING

Oscar J. Vance

Gentlemen, the subject of welding *vs* soldering is controversial, as we all know, but although there has been considerable verbiage on the subject, we have had more experience in soldering and dip-soldering than in welding. Most of the information presented here is based on experience in the military field.

Burroughs Corporation has participated in several major weapon systems programs for which we have used dip-soldering techniques. For the SAGE system, we have built several hundred units of computer and data equipment over the past five years. We are completing our last SAGE unit now. For the SAGE system we have produced well over three-million printed circuit boards using plated-through holes and dip-soldering techniques. We have never had a field failure traceable to either a dip-solder joint or a plated-through hole. We have all the backup data necessary on the program, by the way, and we can prove this.

I will add one other fact. The several hundred computers in the field have a record of being on-the-air—24 hr a day, 365 days a year—for all but 8 min for each computer. This off-the-air time is for shutdowns for a preventive maintenance program. It could be that the computers would run longer. The slides will show you several major types of boards we have used on the program.

The next program we will discuss is the Atlas weapon system. Burroughs was given responsibility for providing a ground guidance computer, which had to be highly reliable. For components in these computers, we used the plated-through hole technique and dip-soldering. One of these computers now in operation at one of the major military installations in this country has a record of somewhere over 15,000 hours of continuous operation without a single malfunction. These ICBM guidance computers were the first solid-state, real-time computers made operational on site by anybody. The computer contains well over 100,000 electronic components.

I might tell you another little story about the computer. It ran through 137 operations at our plant without a single malfunction or failure before it was turned over to the military. One other thing about our Atlas computers: Every major space probe is either range-monitored or guided by a Burroughs computer. We have participated in more than 160 launches at Cape Canaveral. The computers there have never been responsible for a mission failure or held up a launch countdown. Guidance for Project Mercury—putting the astronauts into orbit—is provided by three firms. Computing steering and other commands is done by the Burroughs computer.

The third major program we will discuss is the airborne extension of the SAGE system. I will tell you a little story about this particular computer. The first computer complex—based on the ground—weighed about 40 tons. We have reduced the computer in size till it is less than 1000 lb and contained in aircraft. This particular computer is built by modular construction. Individual modules have been dip-soldered, then attached to the mother board and the mother board dip-soldered, as you will see in the accompanying colored slides indicating several modules in the mother board. Burroughs is presenting a paper at this symposium on this particular technique.

The fourth major program is the research and development system which we are in the process of evaluating from a cost standpoint. This concerns differences between welding and soldering. There has been a lot written on the packing density. In the accompanying photographs, the module on your right is a finished design made at our research center. The module in the center is dip-soldered, top and bottom. The module directly above it shows a technique of welding exactly like soldering; it has the same packing density. These are all the same module—the one on the extreme left is a cleaned-up version of the one on the right. We have produced several thousand of these in a research and development program. We are still producing them . . . we are still evaluating.

Our lab recently told me that from a cost standpoint alone, soldering is about 30% cheaper—from a labor standpoint—than welding. The same module was built of welded technique and also dip-solder technique. The packing density in this particular example is 52 components in each module, including 6 transistors and associated components. This appears to be the highest packing density in production today, even though it is in research production. And it is being produced, not at a research center, but at our production plant in Detroit. Leaving out the cost factor, we find that welding is not more reliable than soldering in this particular application.

Briefly reviewing some of the problems in the welded type of construction, there appears to be no nondestructive way of testing welds. There appears to be no multiple process for generating any more than one weld at a time at the particular module level, whereas at dip-soldering level all joints can be generated at exactly the same time.

I will briefly review the soldering process as used by Burroughs. It is entirely automatic, completely eliminating human error. We use a water soluble flux. The machine dries the flux, dips the board, washes, scrubs, and rinses, completely dries the boards, and ejects the assembly from the machine. We have dipped all sizes of printed circuit boards from postage-stamp size to as large as 11 × 15 without any adjustment in the machine at all. There is absolutely no adjustment to be made. We at Burroughs Military Electronic Computer Division contend that our method of making a soldered joint is more reliable than any other method that has been conceived to date. The reliability of dip-soldering hinges on the removal from the process of the chance for human error, which our particular type of machine does. The machine you will see in the accompanying photographs was developed by Burroughs Corporation.

Our original prototype cost us about fifty thousand dollars to develop. The machine paid for itself in 100 productive days. The new machine that you see in the photographs cost about forty thousand dollars. It is three times as fast. Now, we have no argument with the welding people and we have no scrap with the military. If they wanted us to stick the boards together with conductive chewing gum, we would find a way to do it. But from a cost standpoint—if they are looking at dollars—we can prove that dip-soldering is reliable. We have all the backup data from all the computers we have ever built using this technique.

WELDING

S. Maszy

The state of the art in electronic packaging has advanced so rapidly that serious consideration has had to be given to the methods of making interconnections. The soldering method, which has been used for years and the welding methods that are advancing so rapidly are to be compared and evaluated. Mr. O. Vance of Burroughs, in his paper, will present the soldering point of view. This discussion will emphasize the advantages of welded electronic interconnections over soldered connections.

Resistance-welding and soldering are the most reliable methods for obtaining satisfactory electrical connections when joining interconnecting wires in electronic circuit assemblies. Soldering has predominated in the past for many electronic applications, with the exception of applications in the vacuum tube industry, but the present trend is toward increased use of welding. The trend toward increased use of resistance-welding for electrical connections is sparked by the demand for weight reductions and higher-density electronic circuit modules. Welding permits less weight per installed module because lead, interconnecting, and joint material may be held to a minimum. It has been claimed that soldered joints average 0.031 g heavier than equivalent welded joints. Considering the vast number of connections in some of the more complex electronic equipment, we can see that this factor can produce significant weight reductions. As we all know, even relatively small weight savings assume a tremendous importance when that weight is a factor in establishing a missile's payload.

Welded leads can be shorter because the heat generated during welding of electrical leads is negligible compared with that required for soldering of the leads. Electrical components are susceptible to damage through overheating encountered in the soldering operations. To prevent this, leads must be lengthened to isolate the components and permit the use of soldering irons or flow soldering.

When flow soldering is used, the surface to be soldered must be in a flat uniform plane, requiring additional lead material which otherwise would not be needed. Both of these conditions decrease the package density and increase total circuit weight.

Welding produces cleaner joints than soldering. There is no need for fluxes, with attendant flux-removal problems. In many soldered circuits flux removal has resulted in damage to the delicate components. On the other hand, failure to properly remove soldering fluxes has often resulted in several corrosion problems. In addition, circuits to be encapsulated must be thoroughly cleaned of soldering fluxes. Cleaning fluids and solder fluxes trapped in encapsulated soldered joints can cause failure through corrosion after short periods of time.

To attain high packaging density, it is necessary to make connections close to the components. This is difficult in any type of soldering, and particularly in mechanized flow soldering. The capillary action of the liquid solder and flux control is very critical whenever the joints are within a few thousandths of each other. Under these conditions extreme care must be exercised to prevent formations of soldered connections where they are not required.

Recent advances in the state of the art of soldered connections have produced circuits which approach the weight and size that is accomplished using welded connections, but the package density attainable with soldered connections still does not approach that easily achieved with welded connections.

Packaging of individual circuits in small, inexpensive units is being widely emphasized to reduce maintenance effort in the field. It is much simpler and faster to remove and replace a questionable circuit than to try to isolate the failure within the circuit, disassemble the circuit, and replace defective components. The use of throwaway circuits effectively reduces maintenance costs and reduces down-time. Small inexpensive throwaway circuits, easily produced by resistance welding, cannot be economically produced using soldering techniques.

When soldering connections, it is necessary to closely align the leads and the components. Lead wires must be bent and located properly and sometimes must be held in place until they are soldered and the solder solidifies. This is, of course, time-consuming and often difficult to do without damaging the components. This problem is not encountered in welding connections because each joint is held together and welded at the same time.

Reliability of the electrical connections is naturally the most important factor in selecting the best type of joint. Welded joints in 180° lap-welded nickel ribbon have been shown to be one and one-half times stronger and three and one-half times more consistent in strength than soldered connections in the same type of lead material. It has been proved that structurally sound joints are always electrically acceptable; therefore, reliability of the welded joints will prove superior to soldered joints. Higher physical strength of electrical welded connections is useful and sometimes necessary to resist stresses imposed by encapsulating compounds during encapsulation, and subsequent storage and operation at varying temperatures.

The resistance-welding method of making electrical connections is more scientific than soldering. Soldering is more of an art, and close control of the numerous variables is extremely difficult. Moreover, visual examination of the soldered joint is about the only method of evaluating the joint. In resistance-welded connections, close control over the variables is easily and effectively maintained. Weld schedules, test samples, metallurgical samples, etc. are used to maintain scientific control.

Production costs for quantity runs seems to favor welded connections. Flow soldering requires considerable more capital equipment than the welding. Hand-soldering, although requiring relatively small capital equipment investment, requires a tremendous amount of labor to do an equivalent job. Welding interconnections would probably be in between these two, that is, less capital and less labor. Mechanization of welded-connection operations has been proved feasible and will further increase the advantages of welded connections when fully developed.

In summation, the advantages of resistance-welded electrical connections over soldered connections for packaged electronic circuit applications are greater reliability, lower costs, lower overall labor costs, lower capital equipment investment, less weight, and higher package density.

These advantages undoubtedly verify that welded connections are the most economical means of joining electronic components in limited production. These advantages are further emphasized in the design and production of encapsulated micromodules.

GENERAL DISCUSSION

Q. (Howard Roberts, Hewlett-Packard, Palo Alto, Calif.) I am interested in knowing about this 30% lower cost. Do you have any comment on the lower cost of soldered joints?

A. (Maszy) The lowered cost of the soldered joint, of course, depends on what you have to start with. If you have a flow soldering machine to start with, you have all of your equipment. But, if you have to go out and start from scratch and you don't have a lot of modules to make, there is a breaking point. I doubt that there is that much difference in the cost. I don't believe there is 30%.

A. (Vance) I have one comment to make about that. On one of the weapon system programs that I discussed, we have a requirement to build about 6000 modules in a 24-hr day. We have estimated that it will take more than 200 weld stations in our plant. Workable weld stations, that is. Now the maintenance—the calibrations of weld stations—would mean that you would need about 240 by the time you go through the qualification after the machine has gone down. So the cheapest you can implement a weld station in today's market is about a thousand dollars a work station. That is a quarter of a million dollars. I can do the same job with a forty-four thousand dollar dip-solder machine.

Q. (Martin Camen, Bendix, Teterboro, N. J.) I don't think you can generalize on whether welding or soldering is the cheaper. I think it depends on a specific application and I would like to give an example of this. At Bendix in Teterboro we built two digital computers that were to be used in aerospace applications. The first system was built using only high-density soldered modules. We used the technique that gave us the highest density, namely, cordwood stacking, which I think everybody will agree provides the highest density that can be attained. We built the complete system up in this manner—only solder joints. There wasn't a weld joint in it. We built another system for the same application (aerospace) which used welded joints. The technique we used in the welded module also was one that would give us the highest packing density. It is very similar to the cordwood approach. We found that the welding gave us a considerable reduction in price, mainly in the complexity of putting these high-density modules together. The welding process in the subassembly was completely automatable, whereas in the soldering process it was not.

A. (Vance) I have samples along that we have generated both ways. Now I am not comparing pineapples with apples. I am comparing identical modules. If you want to talk about packing density, we can talk about it—because the component layout is identical whether you weld it or whether you solder it.

Q. (Camen) No, I disagree.

A. (Vance) Well, I can prove it.

Q. (Camen) In your particular technique, you can. Now again, this seems irrelevant. You have to relate the same basic things. I agree that in many applications we found soldering was cheaper but you cannot make a generalization from this. Each technique, each system has to be analyzed to find out which is going to be cheaper.

A. (Vance) Let us stop just a minute and talk about component density. We build the most complicated flip-flop in the business. We take two inverters and put them together because they will buy us more. We will end up with a higher speed machine. Now we can talk about 3-Mc machines because we have 3-Mc machines, big machines. We can produce them tomorrow. Our experience in the welding field didn't start yesterday. We built an airborne computer for the Navy about 5 years ago and we have been researching welding ever since. I might make one other statement that would be of interest to a lot of people here. There is not one piece of welding equipment that you can go out and purchase today, bring it into your shop, and successfully do the job. You have got to rework every one. I know. I have tried every one that exists in this country. I am not speaking just from hearsay because we have done it.

Q. (Camen) I don't want to argue that point because we could go on forever and ever. We have flow solder machines—the latest models—at Bendix, Teterboro, and there is a set of problems involved there, which I think you are well aware of. I am not trying to knock soldering, and I am not trying to knock welding. I think they are both needed and we use both. What I am trying to say is that I don't think anybody can really make a generalization that one is cheaper or better than the other without full knowledge of the system used in a particular application.

A. (Vance) Well, again we will go back just a wee bit to draw on experience. I was fully aware of the first flow solder machine that was ever built in England. Burroughs International told us all about it. I went to New York and took a look at the first one that ever got into this country. We do not own a flow solder machine at our military installation. We have written a series of papers on flow-soldering *vs* dip-soldering. Flow-soldering has an application, but I say our process is entirely foolproof. The biggest thing I have against it is 500+ lb of solder. I talked to people and I asked them how often they change the solder. "Oh, we haven't changed it since we have had the machine. We get all frosty joints." But do you know how often we change the solder in our machines? Sometimes twice a day. We keep a complete series of metallurgical tests running on the solder bath, according to how much the machine is used. There isn't any way to walk off and leave any of these machines to run themselves. It takes controls to do it. Our machines use 110 lb of solder, and we keep a constant check on it. There isn't any easy way to do it; there isn't any easy way to do anything that is going to be reliable.

Q. (Camen) Then again, what you are arguing now is do we flow-solder or dip-solder—which I really don't care about one way or the other.

Moderator (Howard Roberts) I think that we are agreed that whether soldering costs more or less depends on the type of units being made and how many of them. Does anybody want to argue that point? We would like to go back to the point about bringing your welding machine into your shop and not having a good weld. Does anybody have any comments about that?

Q. (Camen) We have about 15 working and we have never had any problem setting them up and getting them working.

Q. (Ed Raymond, Hughes Vacuum Tube Products) I think I would take issue with you on that one statement. I have been selling and handling and working with welding machines for about 8 years and I think when your experiments first started that this was a very true statement. In fact this was before Hughes made welding machines. I say this with all due respect to the competitors. I think that the machines made by the two major companies in the market today can perform a good weld and you can take them right out of the case, set them up, and run them without any trouble at all. The amount of maintenance or down-time that we have had on any machines of our customers that I have been personally contacted has been fantastically small. We have customers who are operating them—in fact, some in this room—24 hr a day, 6 days a week, and with a total spare parts inventory for ten thousand dollar machines of a couple of tubes and a couple of relays. Seriously, no maintenance at all to speak of. So I would like to take issue with you on that particular statement, sir.

A. (Vance) Do you have anything to say about it Maszy?

A. (Maszy) I agree, I think that you can take a machine and set it up and weld with it. We have done it.

A. (Vance) Well, I have one thing to say. Maybe our specs are tougher than yours. I don't know. I rather think to date we have built as many welded modules as anybody in the business. I am sure that we know our problems. The use of any particular manufacturer's welders depends upon the part of the country in which he is doing business. For instance, if I go to the West Coast, I see Hughes and I see Weldamatic. If I go to New England, I see a lot of Raytheon. In discussing welding and welding machines, probably the one man in this country that knows as much about it as anybody is a man by the name of Olsen of Raytheon, Sudbury. I don't know how many people in this room attended the symposium on the Polaris program, but what came out of the program was that the contractors on Polaris were trying to stick together 70 different types of materials, including flat ribbon. Olsen told me in New York, "I am now on an EIA committee to try and standardize on weldable leads for individual components."

I was asked to head up one of the subcommittees and I said absolutely not. I want some component manufacturer to head it up because I don't want to have them say that Burroughs, IBM, and some of the other people rammed a spec down their throat. This is one time I want them to take the lead. I want them to solve this problem. There is a problem that is going to have to be solved because you can't weld any 70 different types with the nugget situation that exists. A lot of people in this audience have heard the stories about nuggets and what you can expect from welders. But, I rather think we at Burroughs have probably one of the toughest specs in the business. We can meet it: it takes a bit of doing. I will not discuss what type of welder we have settled on—this is not fair to any of the manufacturers—but we have definitely settled on a type. We do not care whose welding head, but we are partial to a welding power supply.

Q. (J. J. Bond, Fab-Tool, Englewood, Colo.) Mr. Maszy, you say there is a weight saving on each joint. Don't you inevitably encapsulate all your welded joints anyway and wouldn't this add far more weight than a normal solder joint?

A. (Maszy) Are we talking about encapsulating all of these now, whether they are soldered or welded?

Q. (Bond) We are talking about complete encapsulation.

A. (Maszy) This is right.

Q. (K. A. Allebach, Nortronics, Palos Verdes, Calif.) I would be interested in knowing not the name of this power supply for welding, but for what reasons you have settled upon a particular one?

A. (Vance) Let us say a variable duty cycle time. I have seen a lot of manufacturers with several different types try to meet our particular specification on a duty cycle with their machines and with their power supplies. And, this has been extremely difficult because one particular manufacturer changed his power supplies. In our process of buying 15 or 20 of them, he shipped us some of the new models. Right away we fired them back to him and said he has taken certain parts off it, but these parts are exactly what we need and this is why we need them. He has since put the parts back on his welders because we would not buy the welder without those parts. It will let us do more weld schedules on a particular type of machine.

Q. Mr. Maszy, how do you test your welded joints without destructive testing?

A. (Maszy) We don't. We have a control in the production. Periodically we take samples and pull them.

Q. Each weld being a different spot? I have heard there are 32 variables and only 3 of these are controllable. Is this correct?

A. (Maszy) I didn't know that there are 32 variables.

Q. (Jay M. Block, Hughes Aircraft Co., Culver City, Calif.) I have a couple of comments. In regard to the question just asked about 32 variables—there are not quite that many but there are about 24, of which only 3 are really controllable. Let me qualify—I am a proponent of welding, but there are problems that must be solved and with all the people here, maybe we can do something about it. The gentleman from Burroughs mentioned the fact that he was asked to head a committee to standardize lead materials for components and he said, let the manufacturers do it. Well, we will be waiting a long time because they just have a tendency to be laggard in these types of things. But we are definitely going to require some type of standardization on lead materials if welding is to continue as a basic method of construction of electronic circuitry—and I believe it is going to be. The second thing that I feel is needed is to up-date military specifications to be more realistic with welding problems as found in manufacturing levels, and not try to equate these with spot welding techniques and things of this nature. Resistance-welding, especially cross-wire welding, is a very, very different animal from spot welding, and everybody tries to equate the two. I am just going to put this up as a general question and you can comment as you see fit.

A. (Vance) All you need do is look at the Polaris program. It has gotten completely out of hand and they are trying to stick together 70 different types of materials. For instance, Lockheed on the West Coast has one way and somebody else has another. We build a computer for the Polaris program and we stick it together with solder. We are called upon to build and deliver a complicated computer in 9 months to meet the George Washington sailing date. It had to be installed down through the conning tower of the submarine. This meant that it had to be split in two. We did not have time to design 187 different types of printed circuit boards for it. The particular assembly, in about 18 square inches, has as many as 242 components per board. It is all dip-soldered. We did it with four basic printed circuit boards. We have delivered a computer for every Polaris submarine that is now at sea and those in the future. This is an unheard of thing in our industry. The only reason we could do it is that we built a computer about five years ago, a solid state computer known as Nadac—a naval research computer, but it was based on Nadac. We literally picked it off the shelf. The Polaris computers were delivered in $8\frac{1}{2}$ months—two computers. They were literally built out of our research mill stockroom at our Great Valley Lab. If you look, you will see that every type of transistor packaging that was on the market at that particular time is in that computer. There are all types in there. The computer was literally built out of the stockroom. There was no time to order material.

Q. (Jay M. Block, Hughes) We have something to do with the Polaris program also. I will admit that our first go around was all soldered flat boards and assemblies of that nature. However, we are welding up from here on out and we also do some shipboard computer making now. We are trying to get the particular customer interested in welding from that standpoint, also, and it looks as though he is coming around. The product has an inherently higher reliability despite the criticism that you made on that point. To comment, you said that we had been soldering for a long time but not welding. Well, people walked a long time before they had wheels—but you have to progress.

Q. (Ed Keonjian, American Bosch, Hempsted, N.Y.) I have come here to hear a technical discussion of pros and cons—welding against soldering. Could we continue this approach in typical professional manner?

Moderator (Howard Roberts) Could we go back to the variables in welding? Was there someone who had some more comments on that?

Q. (Walter Prise, Lockheed Missile & Space Co., Sunnyvale, Calif.) I would like to make the following comments. Today, everybody talks about reliability. Reliability seems to be the most important item in our military installations, etc. I felt that Mr. Vance gave a very good comparison between welded and soldered reliability. I would like to hear from somebody else, particularly the gentleman from Martin. Can we have definite reliability figures in welding? I don't mean just saying it is higher or lower. Let us have a comparison study indicating the parameters of the study and then results between the soldered and welded modules.

Moderator (Howard Roberts) Has anyone else built five computers that will work for 100 million hours using welded joints? (Pause) No figures on the reliability of welded joints?

A. (Maszy) We have made quite a few modules for the Bull-Pup program and also for some of our research and development and we have had very good reliability. We have had no failures, to my knowledge.

Q. (Joe Ritter, Electronic Modules Corp., Timonium, Md.) I would like to get into this controversy. There are a number of comments I want to make. These aren't in the nature of questions. I just want to throw them out for discussion. One statement was made that we should standardize our lead material, etc. so welding will be a practical process. It seems to me you need more than that. In other words, I have not yet heard any definite advantages to welding. Why go through all these costly evaluations and special materials unless we are buying something from you? Right now I haven't heard anything to show that we are. There is another area that I think should be touched on: maybe we are overemphasizing the module a little. When we talk of reliability there are a lot of factors involved besides the method of interconnection. The production process is important too. You can get a solder joint or a weld joint failure because of how you put them together, not because the method was inherently good or bad. If either process is done correctly you should get reliability out of it. I think that is a basic assumption. One is not better than the other because they are based on different processes. You have to use good processes for each. As far as reliability is concerned, I would like to throw out some figures that I have brought with me. This is an independent test being performed at Battelle Institute for the Signal Corps on 400 different modules that are put together in a system for evaluation. All modules are loaded to full capacity. This is not an operating system. It is just an evaluating system. It is being constantly thermal-shocked and I believe this is the worst environmental condition. It is what separates the men from the boys. It is being constantly thermal-shocked between $-55°C$ to $+80°C$, 24 hr a day. The input voltages are varied $\pm 10\%$. They have accumulated, to date, two and one-half million module hours without any solder joint failures—these are all soldered modules. They intend to run six million hours and the test should be finished sometime at the end of the year. Now, if we are talking about increased reliability I want to know this: how are you going to get any better? There are a number of other points here that Mr. Maszy brought up in talking about weight reduction, size reduction, etc. When we talk about these things, why don't we specify what we are talking about? We need a basis of comparisons. Let us compare the same things. In a potted three-dimensional module, whether it be welded or soldered, we can get the same densities. We can get the same weights. All of these points depend again on the process and the technique. Our experience has been that the soldering process is more than 30% cheaper. I think the only way you can prove this, of course, is for somebody to quote on making the same module both ways or for two people who are competent in each field to quote. I think all of the hypothetical evaluations don't tell you too much. I would like to see this discussion kept on a higher basis than "I can make a better one than you can." Let us put it on the basis that if there is some advantage to welding, then let's find out why there is an advantage and then we can go through all the problems of improving it. But off-hand, I have heard no one give a valid reason for a welded module being superior to a soldered module.

A. (Maszy) Well, if you recall what I said, I specifically brought out the fact that we are talking about small modules. We are looking for weight reduction. I can't understand how you can state that if you take the components from two modules with the same volume, and you solder one and you weld one, they weigh the same. You must have a greater density in one than in the other because you are adding solder to it. And, if you are looking for payload, this means a lot. So this is where you classify density as a consideration.

Q. (Ritter) I disagree with your assumption entirely. As far as I know, all the welded modules that are being used are potted. That is not true of the soldered modules. I don't believe that anybody is putting unpotted welded modules in a system. I may be wrong on that. When you pot, the empty space is taken up with potting materials. I think you will find the weight advantage if there is any, is less than one-tenth per cent in welding. I'd like to make another comment. When you are talking about the susceptibility of components to heat damage, you are talking about experience with semiconductors approximately 5 years ago. There have been improvements in semiconductors. These new semiconductors will take a little more heat than they used to take. You can solder real close to a semiconductor without any degradation, and I think this can be proven. If you would like, we can show you some figures on it.

A. (Maszy) You still have more weight though.

Q. (Ritter) No you don't. I don't see how you can say that.

A. (Maszy) Well, you are adding solder to it. You can't help but have more weight.

Q. (Ritter) Well, you are adding ribbon or some other type of a matrix to it. What are you talking about?

A. (Maszy) Well, I am talking about you taking a welded module and a soldered module and using the same components. You have got the same density there: you are still adding solder to it.

Q. (Ritter) You are telling me now that we have the same density. I am glad you can see this one point. I don't agree with you. I don't know how we can just sit here and argue about it. I would like to show you that it isn't true. We can't do this verbally, but I would like to prove it to you. I think that Mr. Vance has shown you a comparison of his modules, which is one case. I think we can show you the same thing with some modules we made.

A. (Vance) Mr. Maszy has a particular set of specifications to follow. We at Burroughs have a particular set of specifications to follow. The information that both of us have given you here tonight are not criteria to solve your problems because everybody's problems in this room are entirely different. I think you are going to have to put your shoulders to the wheel and solve it yourselves. Now, in the field of potted modules—Is everybody "gooking" them up with the dixie cup process of board epoxy?

Q. (Ritter) No, that is not true.

A. (Vance) There are a few who have done additional work in the field. We have been transfer-molding epoxy. We at Burroughs have been after this for about 3 years now.

Moderator (Howard Roberts) I think discussion of epoxies is getting off the subject again.

A. (Vance) But they talk about potting. As far as weight is concerned, it is about a toss up by the time you fill them with epoxy.

Q. (Ritter) I also want to make a comment about the strength of the joint when you are welding. I guess when you are welding bridges, strength is pretty important. When you are putting a joint in a welded or soldered module that is being potted—and as I said, most of the welded modules that I know of are being potted—the strength of the joint becomes academic. The solder joint may be weaker than the welded one—by whatever margin you choose. But when you put it in a potted package, then the strength is just an academic thing. I don't see that it even enters into the discussion.

A. (Maszy) You are right, after it is potted. But during the potting operation I have seen several of them open up.

Q. (Ritter) Several welded joints?

A. (Maszy) Yes, sir.

Q. (Ritter) Well, I haven't seen this happen in a solder joint if it is soldered correctly.